JEM-EUSO Baseline Optical Design Lens and Frame Stress And Dynamics Analysis

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Reply to Attn of: ES22-11-024

TO: ES11/Roy M. Young

FROM: ES22/Lisa A. Roth

SUBJECT: Extreme Universe Space Observatory (EUSO) Trade Study Results

This memorandum contains the stress and dynamic analysis results from the February/March 2011 trade study on the EUSO lenses and frames. The focus of the analysis for this iteration is to increase the assembly frequency to a minimum of 25 Hz. The next iteration, currently in work, is to maintain this frequency while reducing the mass in the frames.

If you have any questions, please contact the undersigned at 256-544-5503 or via email at lisa.a.roth@nasa.gov.

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EUSO Study Results

The following documents the work performed on the EUSO trade study in February/March 2011. The results are preliminary and identify the areas where more work is needed. The sections contain the following information.

1. Loads - This section shows the load sources and calculations used in the trade study.
2. Material Properties - This section identifies the material properties and sources used in the trade study.
3. Lens Notch Stress Knockdown - This section shows the analysis performed to determine the knockdown factor for the material allowable to use in the stress analysis to account for the notches in the lens. Test results that confirm the knock down are provided.
4. Analysis of One Piece Lens 3 in Frame 3 - This section contains the analysis of the frame 3 with a one-piece lens 3 assembly. The differences from the previous analysis consist of: meeting a design goal of 25 Hz by adding more attachments and frame crossbeams, refining the flexure mesh to match the design, and refining the frame mesh.
5. Analysis of Segmented Lens 1 in Frame 1 – This section contains the analysis of the segmented lens 1 in the frame 1 assembly. In this iteration the lens is mounted in a frame whereas before the lens was mounted directly to the pallet.

Lens 2 is mounted in Frame 2 in a similar manner as Lens 3 is mounted in Frame 3. Therefore, the approach used to increase the frequency for the Frame 3/Lens 3 assembly will also be applicable to the Frame 2/Lens 2 assembly. Due to the similarity between the two assemblies, a stress analysis for the Frame 2 assembly is not expected to uncover any concerns that would not also be seen in the Frame 3 assembly analysis.

In general the majority of the EUSO structure is showing positive margins. There are a few local areas of negative margins that need to be addressed in the next iteration of analysis. None of the negative margins appear to be insurmountable at this time. Most are due to the modeling and will go away when the models are improved in a few key areas. The loads are another area of potential conservatism, with random accelerations applied in all three axes simultaneously. A few minor changes to the design, as well as maturing information on the lens design and loads, should be enough to produce positive margins for the entire structure.

Section 1 - EUSO Loads

The following loads are developed for EUSO Trade Study.

Launch Quasi-Static Accelerations (g's) - NASDA-ESPC-2857 Rev C Table 3.5.5.1.4-1

$Quasi_x := 3.0$ $Quasi_{rx} := 30.0$

$Quasi_y := 3.0$ $Quasi_{ry} := 30.0$

$Quasi_z := 6.0$ (enveloped maximum) $Quasi_{rz} := 30.0$

Random Vibration Accelerations (g's) - NASDA-ESPC-2857 Rev C Table 3.5.5.1.3-1

$PSD := .0178$

$F := 80$ assumed integrated frequency of 80 Hz to maximize acceleration

$Q := 10$ standard damping value assumed

$Random := 3 \cdot \sqrt{\frac{\pi}{2} \cdot PSD \cdot F \cdot Q}$ $Random = 14.188$

These loads are combined per the approach given in the HTV IRD to produce three load sets. Each load can be applied in all +/- combinations in a load set.

Launch Load Combinations (g's) - NASDA-ESPC-2857 Rev C Table 3.5.5.1.4-1

Load Set 1

$Accel_{1x} := \sqrt{Quasi_x^2 + Random^2}$ $Accel_{1rx} := Quasi_{rx}$

$Accel_{1x} = 14.502$ $Accel_{1rx} = 30$

$Accel_{1y} := Quasi_y$ $Accel_{1ry} := Quasi_{ry}$

$Accel_{1y} = 3$ $Accel_{1ry} = 30$

$Accel_{1z} := Quasi_z$ $Accel_{1rz} := Quasi_{rz}$

$Accel_{1z} = 6$ $Accel_{1rz} = 30$

Load Set 2

$Accel_{2x} := Quasi_x$ $Accel_{2rx} := 30.0$

$Accel_{2x} = 3$ $Accel_{2rx} = 30$

$Accel_{2y} := \sqrt{Quasi_y^2 + Random^2}$ $Accel_{2ry} := 30.0$

$Accel_{2y} = 14.502$ $Accel_{2ry} = 30$

$Accel_{2z} := Quasi_z$ $Accel_{2rz} := 30.0$

$Accel_{2z} = 6$ $Accel_{2rz} = 30$

Load Set 3

$Accel_{3x} := Quasi_x$ $Accel_{3rx} := 30.0$

$Accel_{3x} = 3$ $Accel_{3rx} = 30$

$Accel_{3y} := Quasi_y$ $Accel_{3ry} := 30.0$

$Accel_{3y} = 3$ $Accel_{3ry} = 30$

$Accel_{3z} := 1.8 + \sqrt{(Quasi_z - 1.8)^2 + Random^2}$ $Accel_{3rz} := 30.0$

$Accel_{3z} = 16.597$ $Accel_{3rz} = 30$

On-Orbit Quasi-Static Accelerations (g's) - NASDA-ESPC-2857 Rev C 3.5.5.1.4.2

$Quasi_{orbitx} := .2$ $Quasi_{insertx} := 0.0$

$Quasi_{orbity} := .2$ $Quasi_{inserty} := .45$

$Quasi_{orbitz} := .2$ $Quasi_{insertz} := .16$

Acoustic Accelerations - NASDA-ESPC-2857 Rev C Table 3.5.5.1.1-1

Not enough is known about the integrated structure to calculate loads due to the acoustic environment. Therefore, they are not considered in this trade. However, once the structure is more defined, they need to be assessed as acoustic environments have been known to produce significant loads on structures with large surface areas.

Section 2 - Material Properties

The material properties for PMMA vary somewhat in the various sources provided. MAPTIS also contains properties for PMMA. The following summarizes the properties used in the analysis. All but Poisson's ratio are taken from the web site for ShinkoLite provided by Takizawa Yoshiyuki. The Poisson's ratio is taken from the Atoglas Plexiglas Properties. The MAPTIS properties are included to show they are for the most part similar to the vendor data.

$Density := 1.19 \cdot \frac{gm}{cm^3}$ $Density = 0.043 \cdot \frac{lb}{in^3}$

$Modulus := 3200 \cdot MPa$ $Modulus = 4.641 \times 10^5 \cdot psi$

$TensileStrength := 64 \cdot MPa$ $TensileStrength = 9.282 \times 10^3 \cdot psi$

$CTE := .00007$ per 1/C

$Poisson := .35$

The material properties for the frame, 6061-T6, and the flexures, Ti-6Al-4V, are taken from MMPDS-04.

ShinkoLite

SPEC

Average Physical Properties of Shinkolite

Properties						ShinkoliteL	ShinkoliteMR	ShinkolitePX
		JIS	ISO	ASTM	Production method	Continuous casting	Continuous casting	Continuous casting
Specific gravity		ISO 1183 method			g/cm^3	1.19	1.19	1.19
		JIS K 7112	A.C.or D	D792				
Optical	Refractive indexLight transmittance	ISO 489 method				1.49	1.52 (Surface)	1.49
		JIS K 7105	A	D542				
	(Total)	JIS K 7105	ISO 13468-1	D1003	%	93	93	93
	Haze	JIS K 7105	ISO 14782	D1003	%	0.5	0.5	0.5
Mechanical	Tensile strength							
	Rupture	JIS K 7113	ISO 527-2/1B/5	D638	MPa	75	64	74
	Modules of elasticity	JIS K 7113	ISO 527-2/1B/1	D638	MPa	3.2X10^3	3.2X10^3	3.2X10^3
	Elongation at rupture	JIS K 7113	ISO 527-2/1B/5	D638	%	4.5	2.2	4.5
	Flexural strength							
	Rupture	JIS K 7203	ISO 178	D790	MPa	120	91	120
	Modules of elasticity	JIS K 7203	ISO 178	D790	MPa	3.2X10^3	3.2X10^3	3.2X10^3
	Compressive Strength							
		JIS						

	Yield	K 7181	ISO 604	D695	MPa	120	120	120
	Modules of elasticity	JIS K 7181	ISO 604	D695	MPa	$3.2X10^3$	$3.2X10^3$	$3.2X10^3$
	Impact strength (Izod)	JIS K 7110	ISO 180	D256	kJ/m^2	2		1.8
	Impact strength (Sharpy)	JIS K 7111	ISO 179 /1FU	D256	kJ/m^2	17		17
	Rockwell hardness	JIS K 7202	ISO 2039-2	D785		100	100	98
Thermal	Temperature of deflection under load	JIS K 7207 (A)	ISO 75-2/A	D648	°C	100	100	90
	Coefficient of thermal expansion	ISO 11359			$°C^{-1}$	$7X10^{-5}$	$7X10^{-5}$	$7X10^{-5}$
		JIS K 7197	table2	D696				
	Coefficient of thermal conductivity	JIS A 1412		D177	W/mK	0.21	0.21	0.21
	Specific heat	JIS K 7123			J/g°C	1.5	1.5	1.5
Electrical	Surface resistivity 28°C75%RH	JIS K 6911		D257	Ω	$>10^{16}$	$>10^{16}$	$>10^{16}$
	Volume resistivity	JIS K 6911		D257	Ω-cm	$>10^{16}$	$>10^{16}$	$>10^{16}$
	Dielectric strength,short time test	JIS K 6911		D149	kV/mm	20	20	20
	Dielectric constant	JIS K 6911		D150				
	60 cycles					4	4	4
	10E3 cycles					4	4	4
	10E6 cycles					3	3	3
	Power factor	JIS K 6911		D150				

	60 cycles					0.06	0.06	0.06
	10E3 cycles					0.04	0.04	0.04
	10E6 cycles					0.02	0.02	0.02
	Arc resistance	JIS K 6911		D495		No track	No track	No track
Miscellaneous	Flammability (Burning rate)	JIS K6718	ISO 1210	D635	mm/min	33	33	22
	Water absorption (Wt gain on immersion for 24hrs)	JIS K 7209	ISO 62 method 1	D570	%	0.3	0.3	0.3
	Soluble matter lost after immersion				%	0.0	0.0	0.0
	Odor					None	None	None
	Taste					None	None	None
Mar resistance	Tabor abrader (100 times)	JIS K 7204	ISO 9352	D1044	haze%	40	1.5	40

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PLEXIGLAS®

Acrylic Sheet

GENERAL INFORMATION AND PHYSICAL PROPERTIES

ATOGLAS

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INTRODUCTION

Plexiglas® is the acrylic plastic sheet produced by the Atoglas Division of ATOFINA Chemicals, Inc. In its colorless form, Plexiglas acrylic sheet is a crystal clear (with a transparency equal to optical glass), lightweight material having outstanding weatherability, high impact resistance, good chemical resistance, and excellent thermoformability and machinability.

PLEXIGLAS SHEET GRADES

Atoglas supplies various grades of Plexiglas sheet, each manufactured by two distinct processes, each yielding acrylic sheet of exceptionally high quality.

Plexiglas G acrylic sheet is made by a cell-cast process. The hallmarks of Plexiglas G sheet are high performance and the availability of a broad range of colors, patterns, sizes and thicknesses. Plexiglas G sheet conforms to Federal Standard LP-391, Type I, Grade C, and is supplied as an unshrunk sheet. This means that when heated to forming temperatures, it will shrink about 2% in length and width, and will increase in thickness by about 4%.

Plexiglas MC acrylic sheet is made by a proprietary continuous process known as melt calendering. It offers many of the same high-quality features as Plexiglas G sheet, and also has exceptional thickness tolerance and can be thermoformed to greater detail. Plexiglas MC acrylic sheet is well suited to nearly all the conventional uses for which acrylic sheet has long been noted.

Plexiglas Q is made by the same proprietary continuous process used to make original Plexiglas MC sheet. This process ensures exceptional surface finish, optical quality and thickness uniformity. Plexiglas Q has all these attributes of original Plexiglas MC, in addition to enhanced solvent craze resistance. Plexiglas Q is available as standard sheet and reel stock, in thicknesses from 0.110" to 0.177". You can gain additional information in the Plexiglas Q technical brochure.

Plexiglas T combines the beauty of Plexiglas MC with additional toughness gained from the use of our advanced impact acrylic chemistry. This union produces the aesthetics desired with increased toughness. Plexiglas T is more than 50% tougher than standard acrylic sheet. It is available in colorless, white and black, in thicknesses from 0.080" to 0.354". You can gain additional information in the Plexiglas T technical brochure.

FORMS OF PLEXIGLAS SHEET

Aside from colorless sheet, the various grades can come in a variety of transparent, translucent, and opaque colors, as well as in several different surface patterns.

- *White translucent sheet*—A series of standard white translucent colors in a broad density range provides a wide selection of sheet with varying percentages of light transmittance, diffusion, and lamp hiding power. Light transmission also varies with the thickness of the sheet. This product serves well in lighting and sign applications.

- *Translucent colors*—A wide range of standard, brilliant-to-subdued colors that transmit and diffuse light is available. Objects behind the sheet cannot be clearly distinguished. Light transmittance does not depend on sheet thickness. Translucent color sheet is suitable for most sign applications.

- *Transparent colors*—A selection of standard colors that provide see-through, color filtering, and solar heat and glare control is available. Light transmittance varies from color to color, but for the same color remains about the same value, regardless of sheet thickness. Typical applications include glazing, displays, and fixtures.

- *Opaque colors*—Standard opaque low-chroma colors for non-illuminated decorative panels are available.

- *Solar control colors*—These sheets solve solar heat and glare control problems. Available in bronze and gray tints, they provide a high level of protection for architectural and transportation glazing, enclosures, and sunscreens. As with other transparent colored sheet, the light transmittance varies from color to color, but sheet of the same color transmits light about the same intensity, regardless of its thickness.

- *Patterned sheets*—The surface texture of patterned Plexiglas sheet refracts or bends transmitted light. Adding special textures provides decorative effects, diffuses annoying reflections, and permits privacy. Certain surface texture patterns come on one or both sheet sides, and in transparent, translucent, and opaque colors.

Standard Patterns	Description
P-4	prism (approx. 64/sq in, G only)
P-5	ripple design (one side, G only)
DP-30	stipple (both sides)
DP-32	Flair® (both sides, MC only)
P-95	fine matte finish
Non-Glare	for framing market (MC only)

- *Infrared transmitting*—Colorless Plexiglas sheet transmits most of the invisible near-infrared energy; however, Plexiglas G sheet color 3143 blocks visible light and selectively transmits infrared light. Applications include remote control devices, laser lenses, and heat sensors.

- *Ultraviolet light filtering*—The Plexiglas G, UF-3 and UF-4, and the Plexiglas MC UF-5 sheet formulations block ultraviolet (UV) light, with UF-5 providing maximum UV absorbance. Standard Plexiglas sheet grades only absorb the short UV wavelength energy; however, the UF formulations have the same physical properties as their corresponding sheet grades, and are often used for displaying documents and artifacts to minimize the harmful effects of ultraviolet light.

APPLICATIONS

Plexiglas sheet is a versatile material that has many residential, commercial, industrial, and professional uses. Major applications fall into such categories as architectural glazing, retail display, signs, lighting, noise reduction, industrial guards, restaurant fixtures,

and document preservation. The listing that follows is merely a sample.

- point-of-purchase displays
- trade show exhibits
- map/photo covers
- architectural glazing
- art/document preservation
- vehicle glazing
- framing medium
- electronic equipment panels
- machine glazing
- safety glazing
- infrared windows
- retail display fixtures and cases
- brochure/ad holders
- lenses
- noise shields
- pediatric incubators
- splash guards
- industrial safety guards
- transparent tanks
- lighting fixture diffusers
- transparent lids
- outdoor luminous signs
- transparent equipment
- street lighting shields
- models
- restaurant sneeze guards
- demonstration windows and housings
- food containers
- restaurant trays
- tabletop covers

PROPERTIES AND CHARACTERISTICS

BREAKAGE/IMPACT RESISTANCE

Table 1 compares the impact resistance of Plexiglas sheet at different thicknesses with various types of glass. Plexiglas sheet has greater impact resistance than all types of glass, including tempered glass. Data was obtained from test samples one foot square with edges loosely clamped.

The hardness of an object striking Plexiglas sheet affects its impact resistance. The air-cannon impact test gives a practical measure of the impact strength that Plexiglas sheet can be expected to display in service. This procedure measures the velocity and energy required for a projectile of specified weight and tip radius, shot from an air cannon, to break a specimen. Test samples for data in Table 2 are 14" x 20" Plexiglas G sheet, with edges tightly clamped.

Breakage resistance is maximum when the edges of saw-cut sheet or of drilled holes in the sheet are free of notches. Saw blades and drill bits that meet Atoglas specifications will provide notch-free edges, but it may be desirable to finish edges by sanding or scraping, particularly where the sheet is subjected to high impact.

TABLE 1: Impact Resistance of PLEXIGLAS Sheet and Other Materials

Product	Nominal thickness in	mm	Weight of free-falling steel ball lb	F50 energy to break ft-lb
Plexiglas Sheet	.098	2.5	.25	3.0
Plexiglas Sheet	.118	3.0	2.00	4.7
Plexiglas Sheet	.177	4.5	2.00	11.1
Plexiglas Sheet	.236	6.0	5.00	18.1
Window Glass				
Single Strength	.100		.25	0.8
Double Strength	.125		.25	1.8
Plate Glass	.187		.25	2.0
Plate Glass	.250		.25	1.0
Laminated Glass	.250		.25	1.1
Rough Wire Glass				
Impact Rough Side	.250		.25	2.2
Impact Smooth Side	.250		.25	0.2
Polished Wire Glass	.250		.25	0.4

TABLE 2: Air-cannon Impact Test Results for PLEXIGLAS Sheet

Nominal thickness in	mm	F50 energy (ft-lb) to break impacted with: Baseball 0.32 lb	Steel-tipped dart 0.6 lb, 1/2 in. rad. tip
.118	3.0	24 (47 mph)	5
.236	6.0	84 (84 mph)	6
.354	9.0	113 (105 mph)	27
.472	12.0	224 (147 mph)	40
.708	18.0	390 (104 mph)	53
.944	24.0	505 (220 mph)	68

CHEMICAL RESISTANCE

Both Plexiglas G and MC sheet have excellent resistance to most chemicals, including solutions of inorganic alkalies and acids, such as ammonia and sulfuric acid, and aliphatic hydrocarbons, such as hexane, octane and VM&P naphtha.

Plexiglas G and MC sheet do differ somewhat in their resistance to certain chemicals, as indicated in Table 3. Both grades are attacked by aromatic hydrocarbons and dissolve in organic compounds such as acetone, benzene, and toluene. Chemical resistance can be influenced by several factors, including stresses generated by fabrication operations and end-use stresses caused by changes in temperature, etc.

Certain gasket and sealant materials, while in contact with Plexiglas sheet, could cause crazing of the sheet under certain conditions. Resistance to stress cracking and crazing is dependent on such factors as total stress on the part, temperature and exposure time; consequently, before using any such materials, the fabricator should test them thoroughly, replicating end-use conditions as closely as possible, to ensure their compatibility.

DIMENSIONAL STABILITY

Plexiglas acrylic sheet will expand and contract with changes in temperature and humidity. Different temperature and/or humidity conditions on the inner and outer surfaces of Plexiglas sheet may cause it to bow slightly in the direction of the higher temperature and/or humidity. However, this type of bowing is reversible. The sheet will return to its original flat state when the temperature and humidity differentials become zero.

Bowing does not affect visibility through flat transparent Plexiglas sheet, but may distort reflections. For translucent or opaque panels in which it is unnecessary to see objects through the sheet, surface textures or formed designs will help disguise specular reflection distortions.

In construction, Plexiglas sheet is often used with other materials that undergo less expansion and contraction. The listing in Table 4 (page 5) compares the coefficients of thermal expansion of Plexiglas sheet with other common construction materials.

To ensure good performance in environments where temperature varies widely, Plexiglas sheet should be installed in a channel frame that permits the sheet to expand and contract freely. The channel frame should be deep enough for the sheet to contract fully and still stay within the frame.

Avoid inflexible fasteners such as bolts that do not permit expansion and contraction. Tapes and sealants that adhere to both the acrylic sheet and the frame should be sufficiently extensible to accommodate thermal expansion of both.

Plexiglas sheet may develop permanent deformation under long-term continuous loading. This cold flow characteristic may be minimized by using thicker sheet, reducing the size of unsupported areas, or using thermoformed configurations.

ELECTRICAL CONDUCTIVITY

Plexiglas sheet is an excellent electrical insulator with a high dielectric constant. This property, however, causes a static charge on the sheet surface, which attracts dust particles and lint. Antistatic compounds can be employed when static buildup and high dust concentration create a cleaning problem.

FORMING

Cold forming

Plexiglas sheet can be cold formed (bent at room temperature) in a smooth arc and held to a radius by forcing the material into a curved channel support.

TABLE 3: Chemical Resistance of PLEXIGLAS Sheet [1]

Weight gain (%) of .236" thick sheet after 7 days immersion at 77°F, ASTM D543 (weight change of 1% or less is considered negligible)

Compound Class	Name	Type [2]	Conc., %	PLEXIGLAS (% weight gain) G .236"	MC .236"
Acids	Acetic	glacial	100	R-S	DL
	Acetic		5	0.4	0.5
	Chromic		40	0.2	4-D
	Citric		10	0.3	0.4
	Hydrochloric	concentrated	38	0.2	A
	Hydrochloric		10	0.3	0.4
	Hydrofluoric		40	8.5E	—
	Nitric	concentrated	70	A-D	A
	Nitric		40	2.8	5-A
	Nitric		10	0.3	0.4
	Oleic		–	0.0	-0.1
	Sulfuric	concentrated	98	D-R-S	DL
	Sulfuric		30	0.2	0.3
	Sulfuric		3	0.4	0.5
Bases	Ammonium hydroxide	concentrated	28	0.2	0.3
	Ammonium hydroxide		10	0.4	0.5
	Sodium carbonate		20	0.2	0.3
	Sodium carbonate		2	0.4	0.5
	Sodium hydroxide		60	-0.2	-0.4
	Sodium hydroxide		10	0.3	0.4
	Sodium hydroxide		1	0.4	0.5
Commercial	Cottonseed oil	edible grade		<0.1	0.1
Products	Detergent solution	heavy duty		0.25	0.5
	Kerosene	No. 2 fuel oil (ASTM D396)		<0.1	0.1
	Mineral oil	white, USP		<0.1	0.1
	Lacquer thinner			DL	DL
	Olive oil	edible grade		<0.1	0.1
	Soap solution	white flakes		1	0.5
	Transformer oil	(ASTM D1040)		<0.1	0.1
	Turpentine	distilled spirit (ASTM D13)		<0.1	0.1-C
Inorganic	Distilled water			0.4	0.6
Compounds	Hydrogen peroxide		28	0.4	0.8
	Hydrogen peroxide		3	0.4	0.6
	Sodium chloride		10	0.3	0.5
	Sodium hypochlorite		5	0.3	0.4
Organic	Acetone			DL	DL
Compounds	Aniline			DL	DL
	Benzene			DL	DL
	Carbon tetrachloride [3]			<0.1	A-E
	Dibutyl sebacate			0.1	0.1
	Diethyl ether			<0.1-C	R-S
	Dimethyl formamide			DL	DL
	Ethyl acetate			DL	DL
	Ethyl alcohol		95	1.4	4.0
	Ethyl alcohol		50	0.8	2.0
	Ethylene dichloride			DL	DL
	2-Ethylhexyl sebacate			<0.1	0.1
	Heptane			0.0	0.1
	Isooctane			<0.1	0.1
	Isopropyl alcohol		99	0.1	C
	Methyl alcohol			5.8-S	A
	Phenol (aqueous)		5	A-C	A
	Toluene			DL	DL

Chemical Resistance Code:

A = Attacked
C = Crazed
D = Discolored
DL = Dissolved
E = Edge Swelling
R = Rubbery
S = Swollen

Weight change is affected by the thickness of the material. Values given are for .236" thickness.

(1) Values given are averages and should not be used for specification purposes.

(2) Samples conditioned per ASTM D618, Procedure B, except where noted.

(3) Although exposure to carbon tetrachloride causes only negligible weight change in Plexiglas sheet, it does cause optical distortion of the surface. Carbon tetrachloride should NOT be used on Plexiglas sheet.

TABLE 4: Coefficients of Thermal Expansion

Product	Inches/Inch/°F
Plexiglas sheet	.0000410
Aluminum	.0000129
Copper	.0000091
Steel	.0000063
Plate glass	.0000050
Pine, along grain	.0000030
Pine, across grain	.0000190

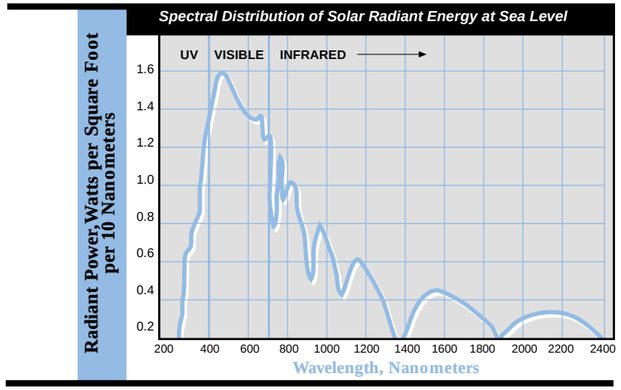
TABLE 5: Recommended Minimum Radii of Curvature for Cold-formed PLEXIGLAS Sheet

Nominal sheet thickness (in)	(mm)	Recommended minimum radius (in) PLEXIGLAS G	PLEXIGLAS MC
0.060	1.5	11	N.A.
0.098	2.5	17.5	29
0.118	3	21	35
0.177	4.5	32	53
0.236	6	42.5	71
0.354	8.5	60	100
0.472	12	86	143

Radii of curvature less than those specified may exceed the design stress limits for the material, resulting in crazing.

N.A. = Not Applicable.

FIGURE 1



The recommended radius of curvature should be a value greater than 180 times the thickness of the sheet for Plexiglas G sheet, and 300 times the thickness for Plexiglas MC sheet (see Table 5).

Hot forming

In the case of hot forming, Plexiglas sheet becomes soft and pliable at its forming temperature: approximately 325° F. After being formed, the sheet cools and hardens, retaining the new shape.

Because Plexiglas sheet forms at low pressure, molds can be made of low-cost wood and plastic. This permits complex, custom-designed panels in small quantities at a reasonable tooling cost.

Hundreds of formed panels can be made in the same mold without loss of quality in the finished part.

Design stresses

Plexiglas sheet has good tensile and flexural strength properties. However, stress considerably below the values shown in Table 12 (page 10) will produce light surface cracks known as crazing. To avoid stress-crazing, design limits for continuously imposed loads should not exceed 1,500 psi for Plexiglas G sheet and 750 psi for Plexiglas MC sheet. Stresses of greater magnitude but short duration will not generally cause stress-crazing.

RESPONSE TO ELECTROMAGNETIC RADIATION

Visible light transmittance

In colorless form, Plexiglas sheet is as transparent as the finest optical glass. Its total light transmittance is 92%, and haze measurement for colorless Plexiglas sheet averages only 1%.

The wavelengths of visible light fall between approximately 400 and 700 nanometers in the electromagnetic spectrum. Electromagnetic energy reaching the earth from the sun is rich in these wavelengths, tapering off in the ultraviolet and infrared regions as shown by the relative energy distribution curve in Figure 1.

When light energy strikes colorless Plexiglas sheet perpendicular to the surface (0 degree angle of incidence), most is transmitted, part is reflected at each surface, and a negligible fraction is absorbed (Figure 2).

The theoretical maximum transmittance of a nonabsorbing optical medium depends on its refractive index. Plexiglas sheet has a refractive index of 1.49; the calculated theoretical maximum light transmission

FIGURE 2

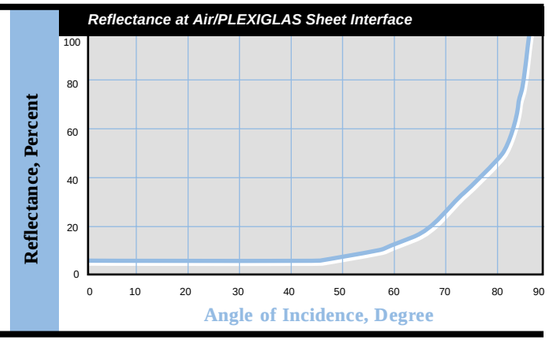
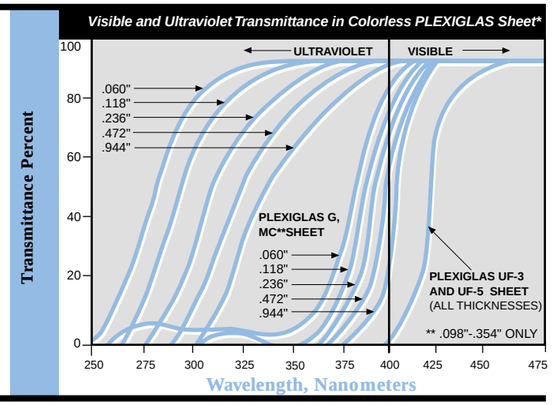


FIGURE 3



The curves in Figure 3 are typical for these materials; however, values can change slightly with formulation modifications and, therefore, should not be used for specification purposes.

for such a medium is 92.3%. Actual measurement shows that colorless Plexiglas sheet as thick as six millimeters (0.236") transmits 92% of perpendicular rays; this represents virtually all the light that could be transmitted by a perfect optical medium of this refractive index.

Approximately 4% of the incident perpendicular rays are reflected on passage through each surface of colorless Plexiglas sheet, giving a total reflectance loss of approximately 8%. As the angle changes, reflectance increases and the transmittance decreases.

The data in Tables 6 and 7, to the right, present transmittance values for colorless, white translucent, and transparent gray and bronze Plexiglas sheet in its full range of densities.

In all ordinary thicknesses, the light absorbance of colorless Plexiglas sheet is not significant. Even at a thickness of one inch, absorbance is less than 0.5%.

TABLE 6: Solar Energy and Visible Light Transmittance of White PLEXIGLAS Sheet

	Solar energy transmittance (%)	Light transmittance (%)		
White tl color no.	0.177" thick (4.5 mm)	0.118" (3 mm)	0.177" (4.5 mm)	.236" (6 mm)
Colorless	85	92	92	92
W-2067	66	71	61	52
W-2159*	62	64	53	43
W-2254*	59	60	50	41
W-2447	52	50	42	35
W-7138	37	41	33	26
W-7328	27	31	23	17
W-7420	18	22	15	11
W-7508	8	8	6	4

*Custom color.

TABLE 7: Solar Energy and Visible Light Transmittance of PLEXIGLAS Sheet–Solar Control Colors

Color number	Transmittance (all thicknesses)	
	Solar energy	Visible light
Colorless	85%	92%
Gray #2538	27%	16%
Gray #2537	41%	33%
Gray #2064	36%	27%
Gray #2074	24%	12%
Gray #2094	55%	45%
Gray #2514	62%	59%
Gray #2515	74%	76%
Bronze #2370	20%	10%
Bronze #2412	35%	27%
Bronze #2404	56%	49%
Bronze #2539	62%	61%
Bronze #2540	75%	75%

Ultraviolet transmittance

Plexiglas sheet absorbs short wavelength ultraviolet (UV) energy, but transmits most of the long wavelength UV (those wavelengths just short of the visible region), Figure 3.

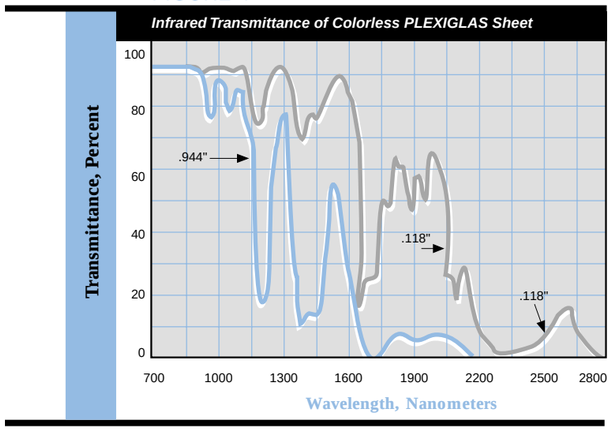
This UV stability gives Plexiglas sheet superb weatherability and makes it the logical choice for outdoor and artificial lighting applications.

The absence of visible changes in Plexiglas sheet after prolonged outdoor or artificial light exposure means that no change has taken place in the spectrophotometric characteristics of the material in the ultraviolet and visible ranges. Plexiglas sheet exhibits an increase in UV absorbance caused by sunlight. Most of the drop in UV transmittance of Plexiglas sheet takes place in the first two years. Absolutely no change occurs in the spectrophotometric curves of these exposed samples between 5 and 10 years outdoors.

Colorless Plexiglas sheet exhibits the same excellent resistance to discoloration when exposed for 20 years or more to constantly lit fluorescent lamps, even when the Plexiglas sheet is only two inches from the lamp.

Some applications, such as document preservation, call for a filter material that absorbs more UV energy than ordinary glass without absorbing visible light. Plexiglas G UF-3 and Plexiglas MC UF-5 acrylic sheet absorb 98% of all UV rays, as well as some visible light. Plexiglas G UF-4, developed for mercury vapor lighting applications, can also be used as a protective shield. Plexiglas G UF-4 sheet does transmit slightly more UV energy than Plexiglas G UF-3 and Plexiglas MC UF-5 sheet.

FIGURE 4



Infrared transmittance

Colorless Plexiglas sheet transmits most of the invisible near-infrared energy in the 700 to 2800 nanometer region, but it also absorbs certain bands as shown in Figure 4. The curves for 0.118" and 0.944" thick colorless Plexiglas sheet show that near-infrared transmittance depends on thickness, decreasing logarithmically as thickness increases.

At infrared wavelengths longer than 2800 nanometers and as long as 25000 nanometers, and in thicknesses greater than 0.118", colorless Plexiglas sheet is entirely opaque. At thicknesses less than 0.118", Plexiglas sheet transmits small amounts of infrared energy at certain wavelengths within this region. All standard formulations of colorless Plexiglas sheet have the same general infrared transmittance characteristics.

Sensitive instruments confirm that weathering produces no change in the infrared transmittance characteristics of Plexiglas sheet.

Plexiglas G 3143 custom-colored sheet selectively transmits infrared light. Applications for this material include remote control devices, laser lenses, and heat sensors.

X-ray transmittance

Colorless Plexiglas sheet readily transmits X-rays in all ordinary thicknesses. Plexiglas sheet has essentially the same X-ray absorption coefficient as water. X-ray photographs can be taken of knitting bone fractures without removing the acrylic splints.

Radio frequency transmittance

Most formulations of colorless Plexiglas sheet readily transmit standard broadcast and television waves as well as most radar bands.

High-energy radiation

Although Plexiglas sheet possesses unusual resistance to discoloration from exposure to all ordinary light sources, special sources that emit a combination of

TABLE 8: Noise Reduction Values for PLEXIGLAS Sheet

(Test panels were 75" x 100")

Frequency spectrum of noise source	Approximate noise reduction - dB(A) Sheet thickness (in) .118* (3mm)	.236 (6mm)	.472 (12mm)	.944 (24mm)	double glazed**
Low frequencies predominant	15	21	26	30	34
Flat frequency spectrum	25	29	33	35	38
High frequencies predominant	28	31	34	36	40

* Estimated from measurements of .236", .472", and .944" sheet.
** 0.236" Plexiglas sheet, air space, 0.177" Plexiglas sheet.

TABLE 9: STC Noise Ratings of PLEXIGLAS Sheet

Construction thickness	STC
Plexiglas sheet (0.118")*	25
Plexiglas sheet (0.236")	29
Plexiglas sheet (0.472")	33
Plexiglas sheet (0.944")	35
Plexiglas sheet [(0.236") air space (0.177")]	38

*Estimated from measurements of .236", .472", and .944" sheet.

intense, high-energy radiation plus visible light may in time discolor and even physically degrade Plexiglas sheet.

Under normal exposure conditions, visible light and UV radiation do not affect the optical properties of Plexiglas sheet, but UV radiation between 280 and 400 nanometers, if sufficiently intense or persistent, will cause slight yellowing. Light sources that may produce this type of energy include sunlamps and mercury vapor lamps.

Discoloration induced by the high UV emissions of some mercury vapor lamps is best resisted by the special colorless formulation, Plexiglas G UF-4 sheet.

Germicidal or sterilizing radiation (approximately 260 nanometers) attacks all types of Plexiglas sheet and most other organic materials. This short wavelength UV radiation has a very high energy content capable of physically damaging Plexiglas sheet. For this reason, acrylic parts should be shielded from direct exposure to radiation produced by germicidal lamps such as those used in vending machines.

High energy ionizing radiation of the type encountered in outer space or in nuclear experiments is usually harmful to Plexiglas sheet, causing discoloration, physical deterioration, or both. The specific reaction of Plexiglas sheet closely depends on the nature of the radiation, its intensity and duration. The behavior of acrylic sheet and other plastics on exposure to ionizing radiation has been discussed in the scientific literature.

Nuclear radiation transmittance

Colorless Plexiglas G sheet has the following nuclear transmittance characteristics:

- *Alpha rays*—Generally opaque, exhibiting essentially 100% absorption at all thicknesses.
- *Beta rays*—Essentially opaque at thicknesses of 0.334" or more.
- *Gamma rays*—Transparent to gamma rays in all ordinary thicknesses. Colorless Plexiglas sheet has about the same gamma ray absorption coefficient as water; however, high dosage and intensity, as is common in sterilizing, may cause discoloration or even the loss of some physical properties.
- *Neutrons*—Opaque to neutrons. Plexiglas sheet serves as a neutron stopper with stopping power that varies directly with hydrogen content (8%).

TABLE 10: Comparison of Noise Reduction Characteristics of PLEXIGLAS Sheet With Other Materials

Construction material thickness	Approximate noise reduction*- dB(A)
Plexiglas sheet (0.118")	25
Plexiglas sheet (0.236")	29
Plexiglas sheet (0.472")	33
Plexiglas sheet (0.944")	35
Double glazed Plexiglas sheet	38
Glass (1/8")	25
Glass (1/4")	27
Plywood (1")	26
Steel (1/8")	37
Sheet lead (1/16")	38
Wood stud partition	38

**Noise reduction obtained in enclosures depends on the completeness of the enclosure, tightness of joints, etc. The above dB(A) noise reductions were obtained in a completely enclosed, tightly joined structure. These conditions are seldom achieved in the real world; however, even under more realistic conditions, the use of Plexiglas sheet barriers can reduce noise levels enough to protect against heavy damage. The main purpose of this Table is to indicate the relative noise reduction capabilities of commonly used materials in terms of dB(A).*

LUMINOUS COLOR EFFECTS

Plexiglas sheet comes in a wide range of translucent and transparent colors that withstand the effects of sunlight and other elements extremely well. As a result, back-lighted Plexiglas sheet panels are very effective in outdoor/indoor lighting and display treatments.

SOUND TRANSMISSION

Plexiglas sheet offers sound loss characteristics that are equal to or better than those of glass. Since Plexiglas sheet is also more resistant to breakage, it can be used as a transparent sound barrier to reduce noise levels and increase safety at the same time. Tables 8, 9 and 10 (on page 8) show noise reduction values and STC ratings for Plexiglas sheet and other construction materials.

RIGIDITY

Plexiglas sheet is not as rigid as many other materials used in building and construction. The sheet may buckle under load and contract as a result. Users can avoid problems of this sort by adhering to the following guidelines:

- Channels engaging the edges of Plexiglas sheet must be sufficiently deep to allow for contraction from deflection under load, as well as thermal expansion and contraction.
- Forming Plexiglas sheet increases its rigidity. Wherever practical, specify *formed* Plexiglas sheet panels in large unsupported areas where wind or snow loads are possible.
- If it is not practical to form Plexiglas sheet, increasing the thickness of the flat Plexiglas sheet will guarantee greater rigidity.

SERVICE TEMPERATURE

The allowable service temperatures for Plexiglas sheet range up to 200ºF, sufficiently high for fluorescent lighting and exterior applications. But, unless the designer takes certain precautions, Plexiglas sheet should not be installed in applications with incandescent or mercury vapor lamps that exceed these limits. Exposure of Plexiglas sheet to temperatures exceeding 200°F for extended periods of time may adversely affect the physical properties and appearance of the sheet.

WEATHER RESISTANCE

Plexiglas G and Plexiglas MC sheet have a proven ability to withstand the effects of weather, sun, and a wide range of temperatures in outdoor use. This permanence derives from the acrylic resin's inherent stability. A large number of clear samples, after more than 10 years' outdoor exposure in Pennsylvania, show an average of more than 90% light transmission, which represents a loss of only 2%. Inspection reveals that very few test samples exhibit any obvious damage due to weathering.

In other tests, samples of colorless Plexiglas G sheet exposed outdoors in Arizona, Florida, and Pennsylvania for 20 years or more show no significant discoloration, crazing, surface dulling, loss of light transmission, or development of haze or turbidity. Although these samples were Plexiglas G sheet, ongoing weathering studies have shown Plexiglas MC sheet to behave in a similar manner.

In these tests the samples were mounted on outdoor racks at a 45-degree angle facing south. Angling the racks in this manner significantly increases the rigors of exposure. Actual outdoor applications ordinarily involve less severe conditions.

WEIGHT

Plexiglas sheet is less than 50% as heavy as glass and 43% as heavy as aluminum.

TABLE 11: Weight of PLEXIGLAS Sheet, Various Thicknesses

Thickness in	Weight lb/sq ft
0.118	0.73
0.177	1.09
0.236	1.46

TABLE 12: Average Physical Properties of PLEXIGLAS Sheet [1]

Property	ASTM Method[2]	Units	Type of Acrylic sheet PLEXIGLAS G	PLEXIGLAS MC
Thickness, nominal		**in**	**0.236**	**0.236**
Specific gravity	D792	N.A.	1.19	1.19
OPTICAL				
Refractive index	D542	N.A.	1.49	1.49
Light transmittance and haze "as received"	D1003			
Parallel		%	91*	91*
Total		%	92*	92*
Haze		%	1*	2*
After 5 years' outdoor exposure, Bristol, Pa., 45° angle, facing south				
Parallel		%	90*	90*
Total		%	92*	92*
Haze		%	2*	3*
After 240 hours' artificial exposure, Carbon Arc Type, per ASTM G-23				
Parallel		%	90*	—
Haze		%	2*	—
Artificial weathering, fluorescent sunlamp with dew, 10 cycles, 240 hours' exposure	D1501 or Fed. Test Std. 406			
Crazing			none	none
Warping	6024		none	none
Instrumental measurement change in Yellowness Index after artificial weathering	D1925	N.A.	1.0	0.8
Ultraviolet transmission, 320 nm	Beckman DU-792	%	0	0
MECHANICAL				
Tensile strength (0.25" specimen-0.2"/min)	D638			
Maximum		psi	10,500	10,200
Rupture		psi	10,500	10,200
Elongation, maximum		%	4.9	4.5
Elongation, rupture		%	4.9	4.5
Modulus of elasticity		psi	450,000	450,000
Poisson's ratio			0.35	—
Flexural strength (span depth ratio 16, 0.1"/min)	D790			
Maximum		psi	16,000	15,000
Rupture		psi	16,000	15,000
Deflection, maximum		in	0.6	0.5
Deflection, rupture		in	0.6	0.5
Modulus of elasticity		psi	450,000	450,000

TABLE 12 *(continued)*

Property	ASTM Method[2]	Units	Type of acrylic sheet PLEXIGLAS G	PLEXIGLAS MC
Thickness, nominal		**in**	**0.236**	**0.236**
Compressive strength (0.05"/min)	D695			
Maximum		psi	18,000	16,000
Modulus of elasticity		psi	450,000	430,000
Compressive deformation under load	D621			
2,000 psi at 122° F, 24 hrs	Method A	%	0.2	0.3
4,000 psi at 122° F, 24 hrs (Conditioned 48 hrs at 122°F)		%	0.5	0.9
Shear strength	D732	psi	9,000*	—
Shear modulus		psi	167,000	—
Impact strength				
Charpy unnotched @ 73°F	D256	ft-lb/ 1/2" X 1" sect.	7.0	7.0
Izod milled notch @ 73°F		ft-lb/ in. of notch	0.3	0.3
Rockwell hardness	D785	—	M-100*	M-90*
Barcol number	D2583	—	49	—
Resistance to stress				
Critical crazing stress	ARTC Mod.			
Isopropyl alcohol	of	psi	2,100[3]	1,300
Toluene	MIL-P-6997	psi	1,700[3]	1,200
THERMAL				
Hot forming temperature		°F	290-360	275-350
Deflection temperature under (flexural) load	D648			
3.6° F/min-264 psi		°F	205*	200*
Maximum recommended continuous service temperature		°F	180-200	170-190
Coefficient of thermal expansion	E831	in/in/ °F X10^{-5}		
-40°F			2.8	2.7
-20			2.9	2.9
0			3.1	3.1
20			3.3	3.2
40			3.6	3.4
60			3.9	3.6
80			4.2	3.9
100			4.6	4.3
Coefficient of thermal conductivity	Cenco-Fitch	BTU/ (hr)/(sq ft)/(°F/in)	1.3	1.3
Specific heat at 77°F		BTU/ (lb)(°F)	0.35	0.35
ELECTRICAL				
Dielectric strength, short time test	D149	volts/mil	500	500
Dielectric constant	D150		3.7	3.7
60 Hz			3.7	3.7
1,000 Hz			3.3	3.3
1,000,000 Hz			2.5	2.2

TABLE 12 *(continued)*

Property	ASTM Method[2]	Units	Type of acrylic sheet PLEXIGLAS G	PLEXIGLAS MC
Thickness, nominal		**in**	**0.236**	**0.236**
Power factor	D150			
60 Hz			0.05	0.05
1,000 Hz			0.04	0.04
1,000,000 Hz			0.03	0.03
Loss factor	D150			
60 Hz			0.19	0.19
1,000 Hz			0.13	0.13
1,000,000 Hz			0.08	0.07
Arc resistance	D495		No Tracking	No Tracking
Volume resistivity	D257	ohm-cm	6 X 10^{17}	1 X 10^{18}
Surface resistivity	D257	ohm/sq cm	2 X 10^{18}	1 X 10^{17}
MISCELLANEOUS				
Horizontal burning test avg.	D635	cm/min	2.8	2.5
Burning rate		(in/min)	(1.1*)	(1.0*)
Smoke density	D2843	%	4-10	4-10
Flammability classification		UL 94	94HB	94HB
Water absorption, 24 hrs at 73° F	D570			
Weight loss on drying		%	0.1*	0.1*
Weight gain on immersion		%	0.2*	0.3*
Soluble matter lost		%	0.0*	0.0
Water absorbed		%	0.2*	0.3*
Dimensional changes on immersion		%	0.0*	0.0*
Water absorption (weight gain) after immersion for:				
1 day	D229	%	0.2*	—
2 days	and	%	0.3*	—
7 days	D570	%	0.4*	—
28 days		%	0.8*	—
56 days		%	1.1*	—
84 days		%	1.3*	—
Humidity expansion, change in length on going from 20% to 90% relative humidity at equilibrium, 74°F		mils/in	3	—
Odor			None	None
Taste			None	None

* This value will change with thickness. The value given is for the thickness indicated in the column heading.
(1) Values reported are averages and should not be used for specification purposes.
(2) Samples conditioned per ASTM D618, Procedure B, except where noted.
(3) The values are after the material has been heated for forming.
N.A. = Not Applicable.

STORAGE AND HANDLING

Plexiglas sheet is shipped in corrugated fiber cartons, or wood-reinforced fiberboard boxes having a gross weight of 400 pounds or more, or on pallets weighing approximately 2,000 pounds. All Plexiglas G and MC sheets are boxed in standard packages. The number of sheets in each package depends on the size and thickness of the sheets.

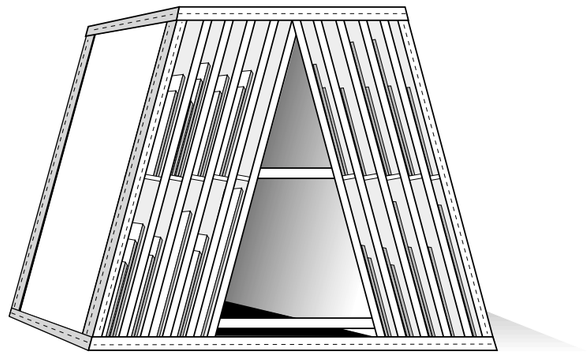
Containers should be handled carefully to prevent damage to the Plexiglas sheet. When possible, forklift trucks should be used to move containers. Otherwise a special hand truck can be constructed or purchased to facilitate safe and economical handling of cases of Plexiglas sheet.

Storage areas should be well ventilated. Air should circulate freely and be relatively moist and cool. The temperature should not exceed 125°F. If Plexiglas sheet is stored in a hot, dry environment or for extremely long periods of time indoors, the adhesive on the masking paper may eventually dry out, making it difficult to remove. Excessive moisture may cause the paper to deteriorate and reduce its effectiveness for protecting the Plexiglas sheet.

Storage areas for Plexiglas sheet should be completely separated from spray-painting booths and other possible sources of solvent vapors. Otherwise the vapors may attack and soften the surface of the sheet.

Packages of Plexiglas sheet should be stored on edge at a 10-degree angle from the vertical. Two-by-three-inch wood strips placed on the floor about 42" apart will keep package edges off the floor and facilitate handling with fork lifts or hand trucks.

FIGURE 5 – A-Frame Rack



Formed sections of Plexiglas sheet must be stored in relatively cool areas. If the parts are to be stacked, they must not be nested, but should be placed in simple frames or racks that fully support the parts so that they will not deform.

MASKED SHEETS

Plexiglas G and MC sheets are supplied with a tough masking paper on both sides. The paper is coated with a pressure-sensitive adhesive that does not attack the Plexiglas sheet surface. Plexiglas MC sheet may also be purchased with a heavy-duty polyethylene masking. The polyethylene clings tightly to the surface without adhesive, so it is easier to remove than paper, and makes the sheet easy to fabricate.

Masking helps prevent accidental scratching during normal handling and fabrication operations, and should be kept in place for most cutting and machining procedures. Although the masking provides a significant degree of protection against surface marring, the fabricator should avoid sliding the sheets over each other or across rough or soiled surfaces.

Paper masking should be removed from both sides of the sheet before it is thermoformed or stored outdoors.

Masked pieces of Plexiglas sheet are best stored on edge in A-frame storage racks as shown in Figure 5. Typically these racks are constructed of plywood and slotted angle iron. The supporting floor of each partition is 1/2" thick plywood. The floor panel may be covered with galvanized sheet metal for increased wear resistance. The rack's A shape equalizes the weight and eliminates stresses on building walls.

These racks give full support to the sheets yet permit easy removal of individual sheets from any rack.

If masked sheets must be stored flat, avoid trapping chips and dirt between the sheets. Plexiglas sheet should not be piled more than 18" high. Small sheets should be stacked on top of the larger ones to prevent unsupported overhang.

It is good practice to store sheets of similar formulation, color, and thickness together. Mark this and other pertinent information on the masking of sheets that have been cut, so they can be identified when needed.

The adhesion of masking paper on the Plexiglas sheet may increase over time, making it difficult to unmask. Use older stock first. Newly received sheets should be placed behind the older sheets in the storage bins.

Masked Plexiglas sheet should never be stored outdoors. Exposure to sunlight and weathering longer than a few days makes removal of masking paper difficult. If it is absolutely necessary to store Plexiglas sheet outdoors, remove the masking paper and cover the sheet with a suitable tape or protective coating.

The masking paper used on Plexiglas sheet is not water repellent. If masked Plexiglas sheet is soaked with water, a white residue may appear on the sheet when the masking paper is removed. To avoid this, store masked sheet where it cannot come into contact with water. If a residue is deposited on the sheet, it may be removed by wiping the surface gently with a clean, soft, damp cloth and drying it with a soft flannel cloth.

UNMASKING

Plexiglas sheet can be unmasked by lifting the masking paper along one edge and rolling it around a dowel or cardboard tube. The paper may be built up on the dowel or tube in successive layers, using the adhesive layer to secure the turned up edge of the masking to the dowel. Remove all residual adhesive from the sheet surface at the time of masking removal. Any residue that remains can be cleaned by wiping with a soft clean cloth dampened with isopropyl alcohol.

Unmasking usually builds an electrostatic charge on the Plexiglas sheet. The electrostatic charge attracts dust and lint to the Plexiglas sheet surface. Eliminate the charge by wiping the sheet with a dampened cloth after unmasking. During dry weather, wet down the shop floor occasionally to minimize dust.

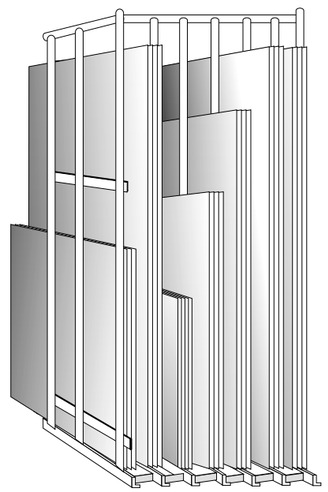
For operations such as a strip heating, cementing, or applying glazing sealants, only the masking paper in the area being worked on should be removed from the sheet. When cutting out small sections of masking paper, take care not to score or scratch the Plexiglas sheet surface underneath. Scoring the sheet may reduce its impact resistance.

Special tools can be employed to minimize the possibility of scoring or scratching the Plexiglas sheet when removing small masking sections (contact Atoglas for information on commercial tools and materials for Plexiglas sheet). When used properly in combination with a suitable solvent, these tools will not score or scratch the Plexiglas sheet.

Masking paper may be difficult to remove in the following circumstances: 1) Plexiglas sheet that has been stored outdoors and exposed to sun and moisture; and 2) sheet that has been stored indoors for lengthy periods or has been exposed to heat or high humidity. When the sheet will be thermoformed, and the masking paper is not adhering too tightly, flash heating the sheet for 60 seconds at 350ºF will loosen the paper enough for easy stripping.

In cases where the paper is sticking more tenaciously, it may be necessary to choose a more aggressive solvent to loosen the masking paper. In such cases, thoroughly soak the masking paper with the solvent, and allow at least 10 minutes for the solvent to penetrate the paper. Strip as described above. If necessary, apply more solvent along the separation line between the masking paper and the Plexiglas sheet.

FIGURE 6–Roller Storage Rack



Use only solvents that will not attack the Plexiglas sheet. A list of recommended solvents for removing masking paper is available from Atoglas. Remove the solvent from the sheet as soon as possible by first washing the sheet with isopropyl alcohol, then with soap and water and, finally, with clear water.

Before attempting to remove tightly adhering masking with solvents, become familiar with the properties of the appropriate solvents and take proper safety precautions. Obtain Material Safety Data Sheets from the manufacturer. Ventilate the work areas as OSHA requires, and prohibit smoking or open flame.

Cases can be stored on edge. Open cases can be stored flat or they can be placed on edge in roller-type racks as shown in Figure 6. Uncased sheets may be stored in A-frame racks. The interleaving tissues should not be removed until the sheets are used.

REMASKING

The masking paper used on Plexiglas sheet will retain its tack and may be replaced if desired. Film masking cannot be reapplied. The adhesive bonds firmly to itself, however, so the coated sides of the masking paper must not be allowed to contact each other. The masking paper can be rolled up in loose tubes and stored on pegs in a clean, dry area. Take care to avoid contaminating the masking paper with dirt to keep from scratching the sheet when the masking paper is reapplied.

Prepared masking papers are available from a number of sources and may be used for remasking. Before using one of these products, however, the user should check its adhesive to be sure it will not attack the Plexiglas sheet.

PROTECTIVE COATINGS

Masking compounds are available that can be sprayed on the Plexiglas sheet and later peeled off. These are especially useful when remasking formed parts.

Use only spray masking compounds by manufacturers that have tested and approved their spray masking for use on acrylic sheet. Some masking compounds may be used indoors for periods as long as 12 months. In general, no masking compound should be used on parts that will be stored outdoors for more than two months.

When using spray masking compounds, apply a coating at least 3-5 mils thick. If the film is too thin, it may be difficult to remove. The film should also be uniform and free from runs and other imperfections.

To remove spray masking from Plexiglas sheet, peel it off or lift a corner of the film and blow a jet of compressed air under it. If the film is hard to remove because it was applied too thinly, apply a fresh coating of the masking compound, let it dry, then remove it. In some cases, it might be necessary to apply a layer of cheesecloth over the fresh spray coating; let it dry before attempting removal. The cheesecloth reinforces the spray coating and makes it easier to remove.

If the protective film has deteriorated because it has been stored outdoors, soaking the coated part in cold water for 24 to 48 hours may help to soften and loosen the film. Stripping compounds supplied by the manufacturers of the spray masking compounds may also be used if they will not craze the Plexiglas sheet.

Remove protective spray masking coatings from Plexiglas sheet parts before the parts are annealed. Otherwise, optical distortions may occur in areas where the thickness or surface of the coating is irregular.

The manufacturers of the protective spray masking should provide the precautions necessary for the safe usage of their products.

PLEXIGLAS SHEET MAINTENANCE

CLEANING

To clean Plexiglas sheet, wash with plenty of nonabrasive soap or detergent and water. Use the bare hand to feel and dislodge any caked dirt or mud. A soft, grit-free cloth, sponge or chamois may be used, but only as a means of carrying water to the sheet. Do not use hard, rough cloths that will scratch the Plexiglas sheet. Dry with a clean damp chamois.

For interior installations, where water cannot be used freely, the Plexiglas sheet should first be lightly dusted (not wiped) with a soft, clean cloth. Then the surface

can be wiped carefully with a soft, wet cloth or chamois. The cloth or chamois should be kept free of grit by frequent rinsing in clean water.

Grease and oil may be removed with kerosene or aliphatic naphtha (no aromatic content).

Do not use solvents such as acetone, benzene, carbon tetrachloride, fire extinguisher fluid, dry-cleaning fluid, and lacquer thinners, since they attack the Plexiglas sheet surface. Do not use window sprays or kitchen scouring compounds.

HEALTH AND SAFETY PRECAUTIONS DURING CLEANING

Some of the chemicals and solvents mentioned here may be toxic if inhaled for extended periods or if swallowed. Provide proper workroom ventilation.

Employees should be protected from skin or eye contact with harmful solvents by use of protective equipment such as impervious gloves, aprons, and splash goggles.

Before attempting to use any solvent or commercial cleaning product, become familiar with its properties and the precautions necessary for its safe use. Material Safety Data Sheets should be obtained from the manufacturer for this purpose.

REMOVING PAINT FROM PLEXIGLAS SHEET

When painting in an area where Plexiglas sheet is stored, the sheet should be covered with paper or drop cloths. If paint splatter or overspray settles on the Plexiglas sheet, attempt to remove it by wiping with isopropyl alcohol. Or soak the paint-covered part in a 10-20% solution of caustic soda or trisodium phosphate and then rinse with water. If the part cannot be soaked, try applying caustic soda or trisodium phosphate solution as a paste made by adding wallpaper paste to the solution.

CAUTION: Caustic soda or trisodium phosphate attacks the skin very quickly. The operator's hands should be shielded by rubber or other protective gloves. Caustic soda or trisodium phosphate can cause permanent injury to eyes. Splash goggles should be worn during use. If caustic soda is splashed into eyes, flush with copious amounts of water and see a physician.

NOTE: Certain types of paints, notably those made with an acrylic resin base, cannot be removed from Plexiglas sheet by the previously described method. For recommendations on how to remove these paints see the Plexiglas Sheet Painting Manual.

CLEANING AIRCRAFT GLAZING

The general guidelines on maintaining Plexiglas sheet also apply to aircraft windows and canopies. However, additional precautions must be observed, because the acrylic glazing is commonly exposed to the chemicals employed to strip paint and brighten, and degrease the aircraft skin. Make sure that chemicals used for this purpose have no solvent or crazing action on the Plexiglas sheet.

WAXING

If, after removing dirt and grease, no great amount of scratching is visible, coat the Plexiglas sheet with a good grade of commercial wax. This process will improve surface appearance by filling in minor scratches. The wax should be applied in a thin, even coat and brought to a high luster by rubbing lightly with a dry, soft cloth, such as cotton flannel, outing flannel, or flannelette.

Excessive rubbing with a dry cloth not only is likely to cause scratches, but it also creates an electrostatic charge which attracts dust particles to the Plexiglas sheet surface. Blotting with a clean, damp chamois or cloth will remove this charge as well as dust.

ANTISTATIC COATINGS

Antistatic coatings successfully prevent the accumulation of an electrostatic charge on Plexiglas sheet parts used indoors for periods of several months. Wiping the surface lightly with a wet cloth will also prevent the buildup of static electricity. Between applications of the antistatic coating, the parts need only be dusted with a soft, clean cloth to maintain a good appearance.

Antistatic coatings can be applied to Plexiglas sheet parts used outdoors before they are first installed. This prevents static buildup when the parts are wiped down after installation. Additional coatings are unnecessary since occasional rain and humidity prevent static accumulation; however, if exterior acrylic parts are dry-wiped frequently, additional antistatic coating applications may be prudent.

Apply liquid antistatic coatings in a uniformly thin coat. If beads appear, the application is too thick; remove the excess with another cloth. Allow the coating to dry, then bring to a high gloss with a soft cloth. When many parts are to be treated, they may be dipped in a thinned solution of the coating.

HAND POLISHING

If, after washing, the Plexiglas sheet surface shows minor scratches, most can be removed or reduced by application of polish. To apply polishes, use a small pad of soft cotton flannel dampened with water. Rub the sheet along the length of the scratches with a back and forth motion (or use a circular motion). Avoid excess rubbing on any one spot. Several applications may be necessary, but most minor scratches can be reduced and the clarity improved within a relatively short time.

When the scratches are removed or considerably reduced, remove the cleaner with a clean, soft cloth, and apply an antistatic coating or wax.

SANITIZING

Plexiglas sheet may be safely and thoroughly sanitized by applying a commercial germicidal compound. An advantage of these high coefficient germicidal materials is that they are effective at room temperatures, so Plexiglas sheet does not have to be heated. Heating may produce undesirable softening effects.

Conventional steam sanitizing at 15 psi is not particularly appropriate, because the heat can deform Plexiglas sheet formed parts. Modification of the conventional procedure sometimes produces a workable system. A succession of relatively short, sanitization passes coupled with an adequate supporting frame for the Plexiglas sheet part will often provide satisfactory results.

Alcohol solutions containing more than 10% alcohol or cresylic acid germicides may attack and harm the Plexiglas sheet surface.

Strong alkali solutions (lye, sodium, ammonium hydroxide, etc.) are extremely effective germicides. Since Plexiglas sheet is very resistant to the effects of strong alkali solutions, they can be used freely.

HEALTH, SAFETY, AND FIRE CONSIDERATIONS

HEALTH AND SAFETY PRECAUTIONS

Some of the chemicals mentioned here may be toxic if inhaled for extended periods or if swallowed. Provide proper workroom ventilation.

Employees should be protected from skin or eye contact with harmful chemicals by use of protective equipment such as impervious gloves, aprons, and splash goggles.

Before attempting to use any commercial sanitizing product, become familiar with its properties and the precautions necessary for its safe use. Material Safety Data Sheets should be obtained from the manufacturer for this purpose.

FIRE CONSIDERATIONS

Plexiglas sheet must be used with an appreciation for the fact that it is a combustible material.

In general, the same fire precautions observed in the handling and use of any ordinary combustible material should be observed when handling, storing or using Plexiglas sheet.

Relevant considerations are: use of the structure (occupancy); location (exposure); height and area; nature of interior arrangements (decorations, finishes and furnishings); availability and construction of fire exits; need for special fire protection systems such as sprinklers, automatic heat and smoke vents, early warning devices and deluge systems or water curtains. Unless there are extenuating circumstances, use sprinkler systems.

FIRE RESPONSE CHARACTERISTICS

The use of Plexiglas sheet is not restricted because of the character of its products of decomposition, but because of its combustibility and burning characteristics.

The ignition temperature of Plexiglas sheet is higher than that of most woods, but it will ignite readily. As for its behavior during combustion, Plexiglas sheet burns vigorously and generates heat rapidly.

Plexiglas sheet softens when heated above 260ºF, which is approximately 300ºF degrees below its ignition temperature. If suspended in air during combustion, Plexiglas sheet will drip burning droplets.

When installed as a wall or ceiling finish or when laminated to a substrate, Plexiglas sheet provides a surface over which flame may spread rapidly and release heat and gases contributing to flashover.

Burning Plexiglas sheet does not produce either excessive quantities of smoke or gases more toxic than those produced by burning wood or paper. The concentration of carbon monoxide and/or carbon dioxide released by burning Plexiglas sheet depends on the quantity of Plexiglas sheet involved and the conditions of burning.

RECOMMENDED PRACTICES

Install Plexiglas sheet away from sources of intense heat or flame. Enclose edges of Plexiglas sheet components. Observe building code stipulations and restrictions. Do not use more Plexiglas sheet than required to perform the function required of it. Employ fire protective systems, such as sprinklers, fire detectors, and automatic vents, as hazard analysis indicates.

Do not use Plexiglas sheet as a supporting element or in any location where resistance to fire penetration is required.

In overhead lighting, mount Plexiglas sheet in free channel mountings to insure fallout prior to ignition. When used in interior window systems, mount the Plexiglas sheet in such a manner as to insure fallout prior to ignition. Extinguish burning Plexiglas sheet with water or fire extinguishers.

Do not install Plexiglas sheet as a wall or ceiling finish or as a substrate surfacing material for large interior surface areas in building applications, unless the areas are protected by an automatic sprinkler system and approval is obtained from the controlling jurisdiction.

BUILDING CODES

Building codes define good practices to follow in the use of Plexiglas sheet for light transmission and control. These practices presume that the combustibility and fire characteristics of the material will receive due consideration during the planning stages of construction. The fire hazard of uses of Plexiglas sheet can be kept at an acceptable level by complying with building codes and observing established principles of fire safety.

Building code regulations may not provide for large-area installations; such installations do not always conform to area limitations. Installations of Plexiglas sheet, such as transparent building enclosures and continuous sections of interior window systems, may require special permits based on an analysis of all relevant fire safety considerations.

On request, Atoglas will provide copies of the approvals of Plexiglas sheet under various building codes. Reports on the status of Plexiglas sheet under Federal Government regulations are also available. Atoglas code consultants and engineers offer assistance in interpreting the codes for installation of Plexiglas sheet in applications that constitute justifiable exceptions to existing restrictions.

A considerable amount of information is available to support such applications. Code reports of general interest include: ICBO Research Recommendation No. 1084 and BOCA Report No. 95-25; SBCCI Report No. 9501; New York City Board of Standards and Appeals Calendars 444-60-SM, 216-63-SM; New York City Department of Water Supply, Gas & Electricity approval for use in signs and lighting fixtures; New York City MEA 107-69-M and MEA 7-93-M.

Plexiglas acrylic plastic is a combustible thermoplastic. Observe fire precautions appropriate for comparable forms of wood and paper. For building uses, check code approvals. Impact resistance is a factor of thickness. Avoid exposure to heat or aromatic solvents. Clean with soap and water. Avoid abrasives.

NOTES

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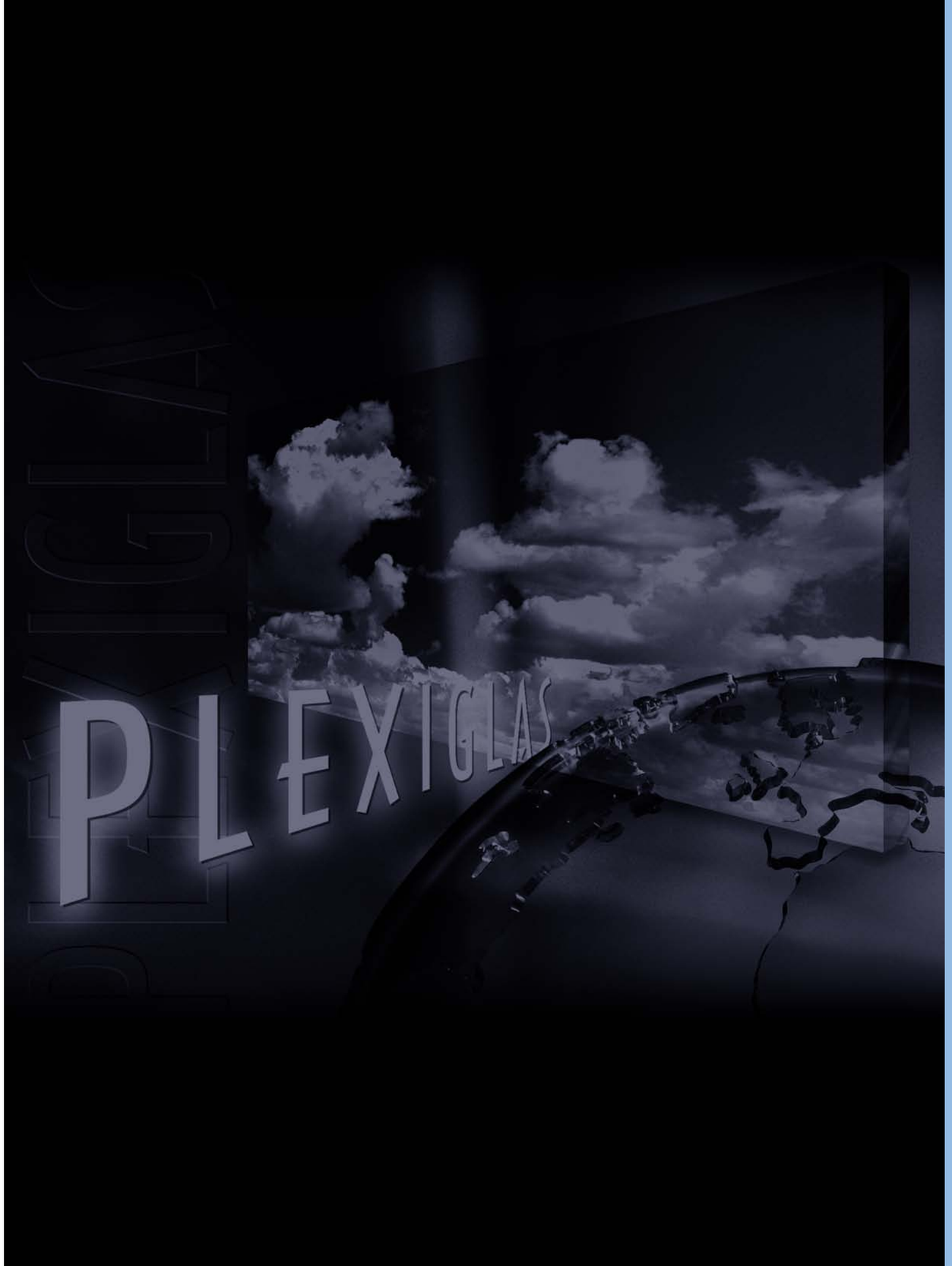

PLEXIGLAS® Acrylic Sheet

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ATOGLAS

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Printed in USA

PMMA - cast sheet (Cast sheet)

General properties

Designation
Polymethylmethacrylate (PMMA) - Cast Sheet
Density
1180 to 1200
kg/m^3
Price
2.58 to 2.84
USD/kg (estimate)
Tradenames
Acrycast; Acrylite; Acrypet; Acryrex; Akrylon; Altuglas; Anjacryl; AtoglasShinkolite; Barlo; Chemcast; Clarex; Clearstat; Comoglass; Degalan; Deglas; Delaglas; Delmore; Delpet; Diakon; Duraplex; Fabback; Goldrex; Implex; Lucite; Lucryl; Metapleks; Optix; Oroglas; Palglas; Panglas; Paraglas; Parapet; Permastat; Perspex; Plexalloy; Plexiglas; Pleximid; Polyman; POLYplex; RepsolGlass; Rohaglas; SewonGlas; Simpex; Solarcote; SolaTuf; Staron; Sumiplex; Taiclear; Umakryl; Umastyr; Vetacril; Vitroflex; XT-Polymer

Composition overview

Composition (summary)
(CH-C(CH3)COOCH3)n
Base
Polymer
Polymer class
Thermoplastic : amorphous
Polymer type
PMMA
Polymer type full name
Polymethyl methacrylate (acrylic)
% filler
0
%
Filler type
Unfilled

Composition detail

Polymer
100
%

Bio-data

Sterilizability (ethylene oxide)
Marginal
note : low H2O avoids crazing
Sterilizability (radiation)
Marginal
note : yellows, but largely reversible by exposure to light (photo-bleaching). Max dose (ref 6) = 10 Mrad and Max dose (ref 7) = 10 Mrad
Sterilizability (steam autoclave)
Poor
note : Distorts
MRI safe
Safe

Mechanical properties

Young's modulus

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2.7 to 2.9

PMMA - cast sheet (Cast sheet)

Compressive modulus
2.68 to 3.27
GPa
Flexural modulus
3 to 3.3
GPa
Shear modulus
1 to 1.2
GPa (estimate)
Bulk modulus
4.32 to 4.54
GPa (estimate)
Poisson's ratio
0.365 to 0.375

Shape factor
5.1

Yield strength (elastic limit)
57.8 to 63.7
MPa (estimate)
Tensile strength
72.2 to 79.6
MPa
Compressive strength
75.8 to 131
MPa
Flexural strength (modulus of rupture)
105 to 116
MPa
Elongation
2 to 7
% strain
Hardness - Vickers
17.3 to 19.1
HV (estimate)
Hardness - Rockwell M
80 to 102

Hardness - Rockwell R
116 to 127
(estimate)
Fatigue strength at 10^7 cycles
15.2 to 16.8
MPa
Fracture toughness
0.7 to 1.6
MPa.m^0.5
Mechanical loss coefficient (tan delta)
0.0138 to 0.0148
(estimate)

Impact properties

Impact strength, notched 23 °C
1.6 to 2.1
kJ/m^2
Impact strength, notched -30 °C
1.9 to 2.1

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kJ/m^2

PMMA - cast sheet (Cast sheet)

Impact strength, unnotched 23 °C
17.6 to 20.7
kJ/m^2
Impact strength, unnotched -30 °C
16.2 to 20.8
kJ/m^2

Thermal properties

Glass temperature
96 to 104
°C
Heat deflection temperature 0.45MPa
101 to 113
°C
Heat deflection temperature 1.8MPa
90 to 103
°C
Maximum service temperature
80 to 105
°C
Minimum service temperature
-75 to -65
°C
Thermal conductivity
0.17 to 0.25
W/m.K
Specific heat capacity
1400 to 1520
J/kg.°C
Thermal expansion coefficient
90 to 162
µstrain/°C
Vicat softening point
103 to 115
°C

Processing properties

Linear mold shrinkage
0.2 to 0.8
% (estimate)
Melt temperature
123 to 260
°C

Electrical properties

Electrical resistivity
3.3e23 to 3e24
µohm.cm
Dielectric constant (relative permittivity)
3.2 to 3.4

Dissipation factor (dielectric loss tangent)
0.05 to 0.06

Dielectric strength (dielectric breakdown)
17.7 to 21.7
MV/m
Comparative tracking index

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600

PMMA - cast sheet (Cast sheet)

Optical properties

Refractive index
1.49 to 1.5

Transparency
Optical quality

Absorption, permeability

Water absorption @ 24 hrs
0.2 to 0.4
%
Water absorption @ sat
1.1 to 2.1
%
Water vapor transmission
1.62 to 1.78
g.mm/m².day
Permeability (O2)
4.31 to 7.19
cm³.mm/m².day.atm
Permeability (CO2)
29.8 to 55.3
cm³.mm/m².day.atm
Permeability (N2)
0.975 to 2.03
cm³.mm/m².day.atm

Durability: flammability

Flammability
Highly flammable
Flammability - typical UL 94 rating
HB
Oxygen index
17 to 19
%

Durability: fluids and sunlight

Env. stress crack index (0=worst, 1=best)
0.49

notes : Reported stress cracking agents (ref. 1). Moderate: 1,2 Dichloroethane, Trimethylpentane/Toluene 5:5, Trimethylpentane/Toluene 7:3, Acetic Acid, Butanol, CH3Cl, Propanol Severe: Amylacetate, Butyl Acetate, Cyclohexanone, Diethylether, Ethylamine, Methanol, Propanol/Toluene 10:1, Propanol/Toluene 3:1
Chem. resistance index (0=worst, 1=best)
0.45

Water (fresh)
Excellent
Water (salt)
Excellent
Weak acids
Acceptable
Strong acids
Unacceptable
Weak alkalis

No warranty is given for the accuracy of this data

Excellent
Boiling Metals
Excellent
Organic solvents
Unacceptable
UV radiation (sunlight)
Good
Oxidation at 500C
Unacceptable
Wear resistance
Acceptable

Chemical resistance to specific chemicals

Chemical resistance, data sources
Derived from Rapra ChemRes record for Acrylic (cast sheet)
Acetaldehyde
Unsatisfactory
Acetic acid (10%)
Satisfactory
Acetic acid (glacial)
Unsatisfactory
Acetic anhydride
Limited
Acetone
Unsatisfactory
Acetonitrile
Unsatisfactory
Acetophenone
Unsatisfactory
Acetyl chloride
Unsatisfactory
Acrylic acid
Doubtful
Aluminum chloride (10%)
Satisfactory
Aluminum sulfate
Satisfactory
Ammonium hydroxide (35%)
Satisfactory
Ammonium sulfate (50%)
Satisfactory
Amyl acetate
Unsatisfactory
Amyl alcohol
Unsatisfactory
Aniline
Unsatisfactory
Antimony trichloride (10%)
Satisfactory
Aqua regia
Unsatisfactory
Arsenic acid
Probably satisfactory
ASTM fuel A
Limited
ASTM fuel B
Doubtful
ASTM fuel C
Doubtful
ASTM oil No. 1

No warranty is given for the accuracy of this data

Satisfactory

PMMA, cast sheet (Cast sheet)

ASTM oil No. 2 or IRM902
Satisfactory
ASTM oil No. 3 or IRM903
Satisfactory
Barium chloride
Satisfactory
Benzaldehyde
Unsatisfactory
Benzene
Unsatisfactory
Benzyl alcohol
Unsatisfactory
Benzyl chloride
Unsatisfactory
Boric acid
Satisfactory
Bromine liquid
Unsatisfactory
Butyl acetate
Unsatisfactory
Butyl alcohol (butanol)
Unsatisfactory
Butyl chloride
Unsatisfactory
Butylamine
Unsatisfactory
Butyric acid
Unsatisfactory
Calcium chloride
Satisfactory
Carbon disulfide
Unsatisfactory
Carbon tetrachloride
Limited
Castor oil
Satisfactory
Cellosolve
Unsatisfactory
Cellosolve acetate
Doubtful
Chloracetic acid
Unsatisfactory
Chlorine dioxide
Doubtful
Chlorine gas (dry)
Limited
Chlorine water
Limited
Chlorobenzene
Unsatisfactory
Chloroform
Unsatisfactory
Chlorosulfonic acid
Unsatisfactory
Chrome plating solution
Satisfactory
Chromic acid
Limited
Citric acid (10%)

No warranty is given for the accuracy of this data

Satisfactory
Five Bi
Probably satisfactory

PMMA - cast sheet (Cast sheet)

Copper sulfate
Satisfactory
Cotton seed oil
Limited
Cresols
Unsatisfactory
Cyclohexane
Limited
Cyclohexanol
Unsatisfactory
Cyclohexanone
Unsatisfactory
Decalin
Unsatisfactory
Diesel oil
Satisfactory
Diethyl ether
Satisfactory
Diethylamine
Unsatisfactory
Diethylene glycol
Satisfactory
Dimethyl formamide
Unsatisfactory
Dimethylamine
Probably satisfactory
Dimethylhydrazine
Doubtful
Dioctyl phthalate
Limited
Dioxane
Unsatisfactory
Ethyl acetate
Unsatisfactory
Ethyl alcohol (ethanol)
Limited
Ethyl chloride
Unsatisfactory
Ethylamine
Probably satisfactory
Ethylene bromide
Unsatisfactory
Ethylene chloride (1,2 dichloroethane)
Unsatisfactory
Ethylene glycol
Limited
Ferric chloride
Satisfactory
Fluoboric acid
Limited
Fluorine (gas)
Unsatisfactory
Fluosilicic acid
Satisfactory
Formaldehyde (40%)
Satisfactory
Formic acid (90%)

No warranty is given for the accuracy of this data

Unsatisfactory
Freon - 11
Limited
Freon - 113
Limited
Freon - 115
Probably satisfactory
Freon - 12
Limited
Freon - 13 B1
Probably satisfactory
Freon - 21
Unsatisfactory
Freon - 22
Unsatisfactory
Freon - 32
Limited
Furfural
Unsatisfactory
Glycerol
Satisfactory
Hexane
Satisfactory
Hydrazine
Doubtful
Hydrobromic acid (50%)
Satisfactory
Hydrochloric acid (10%)
Satisfactory
Hydrochloric acid (36%)
Satisfactory
Hydrofluoric acid (40%)
Unsatisfactory
Hydrogen peroxide (35%)
Satisfactory
Hydrogen peroxide (87%)
Unsatisfactory
Hydrogen sulfide gas
Satisfactory
Iso-octane
Satisfactory
Iso-propyl alcohol (iso-propanol)
Satisfactory
Lactic acid (90%)
Satisfactory
Lead acetate (10%)
Satisfactory
Linseed oil
Satisfactory
Lubricating oil
Satisfactory
Magnesium chloride
Satisfactory
Manganese sulfate
Satisfactory
Mercuric chloride
Satisfactory
Methyl alcohol (methanol)
Unsatisfactory
Methyl bromide (gas)

No warranty is given for the accuracy of this data

Doubtful
Methyl ethyl ketone
Unsatisfactory
Methylene chloride (dichloromethane)
Unsatisfactory
Molasses
Probably satisfactory
Monoethanolamine (2-aminoethanol)
Probably satisfactory
Nickel chloride
Satisfactory
Nitric acid (10%)
Satisfactory
Nitric acid (70%)
Unsatisfactory
Nitrobenzene
Unsatisfactory
Nitromethane
Doubtful
Nitropropane
Doubtful
n-propanol
Satisfactory
Oleic acid
Satisfactory
Olive oil
Satisfactory
Oxalic acid (solutions)
Satisfactory
Ozone (gas)
Limited
Paraffin oil (kerosene)
Probably satisfactory
Perchlorethylene
Limited
Peroxymonosulfuric acid
Unsatisfactory
Petrol (gasoline)
Satisfactory
Phenol
Unsatisfactory
Phosphoric acid (85%)
Unsatisfactory
Picric acid (solutions)
Unsatisfactory
Plating solutions (non-chrome)
Probably satisfactory
Potassium cyanide
Satisfactory
Potassium fluoride
Satisfactory
Potassium hydroxide (50%)
Satisfactory
Potassium permanganate (25%)
Limited
Potassium sulfate
Satisfactory
Propionic acid
Doubtful
Propylene oxide

No warranty is given for the accuracy of this data

Unsatisfactory

PMMA - cast sheet (Cast sheet)

Lime
Unsatisfactory
Rapeseed oil
Satisfactory
Silicone fluids
Limited
Silver nitrate
Satisfactory
Sodium borate
Satisfactory
Sodium carbonate (10%)
Satisfactory
Sodium chloride (25%)
Satisfactory
Sodium chlorite
Unsatisfactory
Sodium cyanide
Satisfactory
Sodium hydroxide (10%)
Satisfactory
Sodium hydroxide (60%)
Satisfactory
Sodium hypochlorite (20%)
Satisfactory
Sodium nitrate
Satisfactory
Sour oil
Probably satisfactory
Stannic chloride
Satisfactory
Styrene
Unsatisfactory
Sulfamic acid (solutions)
Probably satisfactory
Sulfur dioxide (gas)
Satisfactory
Sulfuric acid (10%)
Unsatisfactory
Sulfuric acid (70%)
Unsatisfactory
Sulfuric acid (96%)
Unsatisfactory
Sulfuric acid (fuming)
Unsatisfactory
Tetrachlorethane
Unsatisfactory
Tetrahydrofuran
Unsatisfactory
Tetralin
Unsatisfactory
Thionyl chloride
Doubtful
Titanium tetrachloride
Limited
Toluene
Unsatisfactory
Transformer oil
Satisfactory
Trichloracetic acid

No warranty is given for the accuracy of this data

Doubtful
Nitromethane
Unsatisfactory
Trichlorethylene
Unsatisfactory
Tricresyl phosphate
Unsatisfactory
Triethanolamine
Satisfactory
Triethylamine
Probably satisfactory
Turpentine
Unsatisfactory
Vegetable oils (general)
Satisfactory
Vinyl acetate
Limited
Vinyl chloride
Unsatisfactory
Water (distilled)
Satisfactory
Water (sea)
Satisfactory
White spirit
Satisfactory
Wine
Satisfactory
Xylene
Unsatisfactory
Zinc chloride (aq. sol.)
Satisfactory

Primary material production: energy, CO2 and water

Embodied energy, primary production
93.8 to 110
MJ/kg
CO2 footprint, primary production
3.41 to 3.77
kg/kg
Water usage
108 to 323
l/kg

Material processing: energy

Polymer molding energy
10 to 10.5
MJ/kg
Polymer extrusion energy
3.7 to 3.8
MJ/kg
Polymer machining energy (per unit wt removed)
2.05 to 2.26
MJ/kg (estimate)

Material processing: CO2 footprint

Polymer molding CO2
0.803 to 0.837
kg/kg
Polymer extrusion CO2

No warranty is given for the accuracy of this data

0.296 to 0.304
kg/kg (estimate)

PMMA - cast sheet (Cast sheet)

Polymer machining CO2 (per unit wt removed)
0.164 to 0.181
kg/kg (estimate)

Material recycling: energy, CO2 and recycle fraction

Embodied energy, recycling
48.3 to 49.2
MJ/kg
CO2 footprint, recycling
1.45 to 1.48
kg/kg
Recycle fraction in current supply
0.672 to 0.742
%

Notes

Typical uses
Lenses; light covers; glazing (particularly in aircraft); light pipes; meter covers; bathroom fittings; outdoor signs; skylights; baths; toys.

Commercial grades of approximately similar composition

CAMPUS Plastics grades
39 Linked Record(s)

IDES Plastics grades
375 Linked Record(s)

Further Information

ProcessUniverse
65 Linked Record(s)

Producers
9 Linked Record(s)
- A Schulman Inc.
- Arkema Chemicals, Inc.
- Cyro Industries
- Degussa AG
- Dynachem & Co. Ltd.
- Georgia Gulf Corporation
- Marplex Australia Pty. Ltd.
- Mitsubishi Rayon
- Plastiglas de Mexico

Reference
19 Linked Record(s)

Shape
24 Linked Record(s)

No warranty is given for the accuracy of this data

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Table 3.6.2.0(b_1). Design Mechanical and Physical Properties of 6061 Aluminum Alloy Sheet

Specification	AMS 4026 and AMS-QQ-A-250/11[a]		AMS-QQ-A-250/11[a]	AMS 4025, AMS 4027 and AMS-QQ-A-250/11[a]	
Form	Sheet				
Temper	T4		T42[b]	T6 and T62[c]	
Thickness, in.	0.010-0.249		0.010-0.249	0.010-0.249	
Basis	A	B	S	A	B
Mechanical Properties:					
F_{tu}, ksi:					
L	...	...	...	42	43
LT	30	32	30	42	43
F_{ty}, ksi:					
L	...	...	...	36	38
LT	16	18	14	35	37
F_{cy}, ksi:					
L	...	...	...	35	37
LT	16	18	...	36	38
F_{su}, ksi	20	21	...	27	28
F_{bru}, ksi:					
(e/D = 1.5)	48	51	...	67	69
(e/D = 2.0)	63	67	...	88	90
F_{bry}, ksi:					
(e/D = 1.5)	22	25	...	50	53
(e/D = 2.0)	26	29	...	58	61
e, percent (S-Basis):					
LT	[d]	...	[d]	[d]	...
E, 10^3 ksi	9.9				
E_c, 10^3 ksi	10.1				
G, 10^3 ksi	3.8				
μ	0.33				
Physical Properties:					
ω, lb/in.^{3}	0.098				
C, K, and α	See Figure 3.6.2.0				

a Mechanical properties were established under MIL-QQ-A-250/11.

b Design allowables were based upon data obtained from testing samples of material, supplied in the O or F temper, which were heat treated to demonstrate response to heat treatment by suppliers. Properties obtained by the user may be lower than those listed if the material has been formed or otherwise cold- or hot-worked, particularly in the annealed temper, prior to solution heat treatment.

c Design allowables were based upon data obtained from testing T6 sheet and from testing samples of sheet, supplied in the O or F temper, which were heat treated to T62 temper to demonstrate response to heat treatment by suppliers. Properties obtained may be lower than those listed if the material has been formed or otherwise cold-worked, particularly in the annealed temper, prior to solution heat treatment.

d See Table 3.6.2.0(b_3).

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6061, T6, Sheet, Thickness: 0.01 to 0.25 in, AMS 4025, AMS 4027, A basis

Traceability

See original document
1 Linked Record(s)
Table 3.6.2.0(b1). Design Mechanical and Physical Properties of 6061 Aluminum Alloy Sheet

General

Common Name
6061
Thickness
0.000254 to 0.00635
m
Product Form
Sheet
Condition
T6
Source Figure
3.6.2.0(b1)

Physical & Electrical

Density
2710
kg/m^3

Thermal

Thermal Conductivity
152
W/m.K
Thermal Expansion
0.0000227
strain/°C
Specific Heat
879
J/kg.°C

Elastic

Modulus, L
6.83e10
Pa
Shear Modulus, L
2.62e10
Pa
Comp Modulus, L
6.96e10
Pa
Poisson's Ratio, L
0.33

Tensile

Yield Strength, L
2.48e8
Pa

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Table 5.4.1.0(b$_1$). Design Mechanical and Physical Properties of Ti-6Al-4V Sheet, Strip, and Plate

Specification	AMS 4911[a]						AMS 4904[b]			
Form	Sheet		Plate				Sheet, strip, and plate			
Condition	Annealed						Solution treated and aged			
Thickness, in.	≤ 0.1875		0.1875-2.000		2.001-4.000		≤ 0.1875	0.1875-0.750	0.751-1.000	1.001-2.000
Basis	A	B	A	B	A	B	S	S	S	S
Mechanical Properties:										
F_{tu}, ksi:										
L	134	139	130[c]	135	130[d]	137	160	160	150	145
LT	134	139	130[c]	138	130[d]	137	160	160	150	145
F_{ty}, ksi:										
L	126	131	120	125	118	123	145	145	140	135
LT	126	131	120[c]	131	118	129	145	145	140	135
F_{cy}, ksi:										
L	133	138	124	129	122	127	154	150	145	...
LT	135	141	130	142	128	140	162	...	...	...
F_{su}, ksi	87	90	79	84	79	84	100	93	87	...
F_{bru}, ksi:										
(e/D = 1.5)	213[e]	221[e]	206[e]	214[e]	206[e]	217[e]	236	248	233	...
(e/D = 2.0)	272[e]	283[e]	260[e]	276[e]	260[e]	274[e]	286	308	289	...
F_{bry}, ksi:										
(e/D = 1.5)	171[e]	178[e]	164[e]	179[e]	161[e]	176[e]	210	210	203	...
(e/D = 2.0)	208[e]	217[e]	194[e]	212[e]	191[e]	209[e]	232	243	235	...
e, percent (S-Basis):										
L	8[f]	...	10	...	10	...	5[g]	8	6	6
LT	8[f]	...	10	...	10	...	5[g]	8	6	6
E, 10^3 ksi	16.0									
E_c, 10^3 ksi	16.4									
G, 10^3 ksi	6.2									
μ	0.31									
Physical Properties:										
ω, lb/in.^{3}	0.160									
C, K, and α	See Figure 5.4.1.0(a)									

Last Revised: Oct 2006, MMPDS-03, Item 05-26.

a Mechanical properties also met previous MIL-T-9046, Comp. AB-1.

b Mechanical properties were established under MIL-T-9046, Comp. AB-1.

c A-Basis value is specification minimum. The rounded T_{99} values are as follows: F_{tu}(L) = 131 ksi, F_{tu}(LT) = 132 ksi, and F_{ty}(LT) = 123 ksi.

d A-Basis value is specification minimum. The rounded T_{99} values are as follows: F_{tu}(L) = 133 ksi and F_{tu}(LT) = 133 ksi.

e Bearing values are "dry pin" values per Section 1.4.7.1.

f 8%—0.025 to 0.062 in. and 10%—0.063 in. and above.

g 5%—0.050 in. and above; 4%—0.033 to 0.049 in. and 3%—0.032 in. and below.

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Ti-6Al-4V, Annealed, Sheet, Thickness: 0.02 to 0.025 in, AMS 6945, A basis

Traceability

See original document
1 Linked Record(s)
Table 5.4.1.0(b2). Design Mechanical and Physical Properties of Ti-6Al-4V Sheet, Strip, and Plate

General

Common Name
Ti-6Al-4V
Thickness
0.000508 to 0.000635
m
Product Form
Sheet
Condition
Annealed
Source Figure
5.4.1.0(b2)

Physical & Electrical

Density
4430
kg/m^3

Thermal

Thermal Conductivity
7.27
W/m.K
Thermal Expansion
0.00000882
strain/°C
Specific Heat
548
J/kg.°C

Elastic

Modulus, L
1.1e11
Pa
Shear Modulus, L
4.27e10
Pa
Comp Modulus, L
1.13e11
Pa
Poisson's Ratio, L
0.31

Tensile

Yield Strength, L
9.17e8
Pa

Granta provides **no warranty** for the accuracy of this data

Section 3 - Knockdown in Lens Stress to Account for Notches

The EUSO lenses are made of PMMA plastic. Dimensions are 2600 mm by 2000 mm, as shown in Figure 1. The lens will have multiple 1 mm circumferential cuts for optical reasons. The exact locations of these cuts are not known at this time. Therefore, a model of the cross section of the lens along the longer side was used to determine the stress concentration factor to use as a knock down factor on stresses reported from the smooth lens model. Stress analysis will be performed using a FEM of a smooth lens, and the knockdown factor as determined by the notch stress factor will be used.

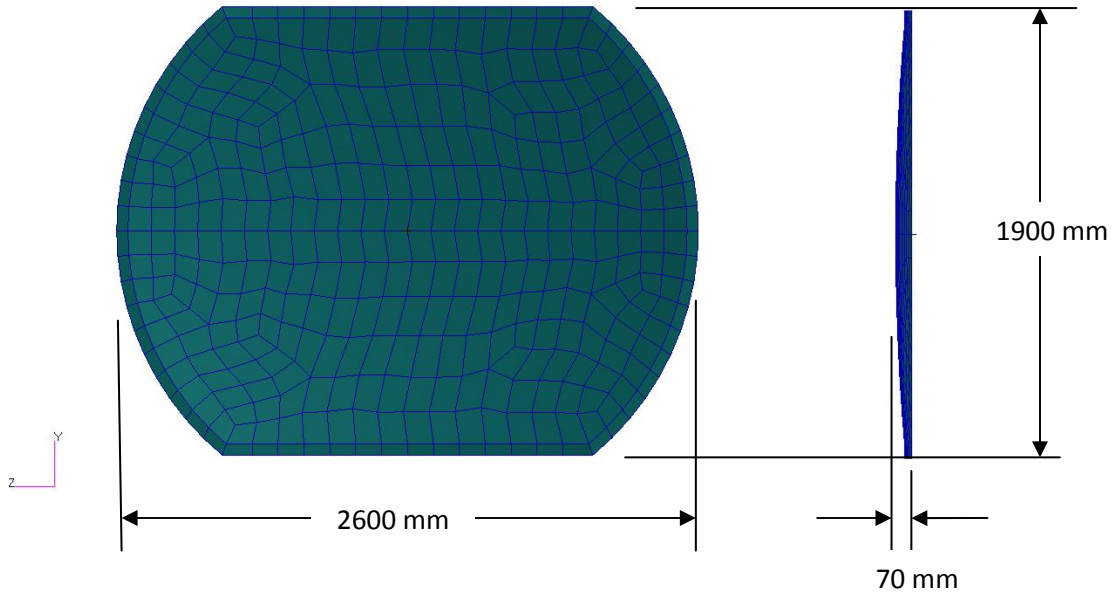


Figure 1 Lens 3 Dimensions

The cross section through the center of the lens was taken to determine the most critical stress concentration factor.

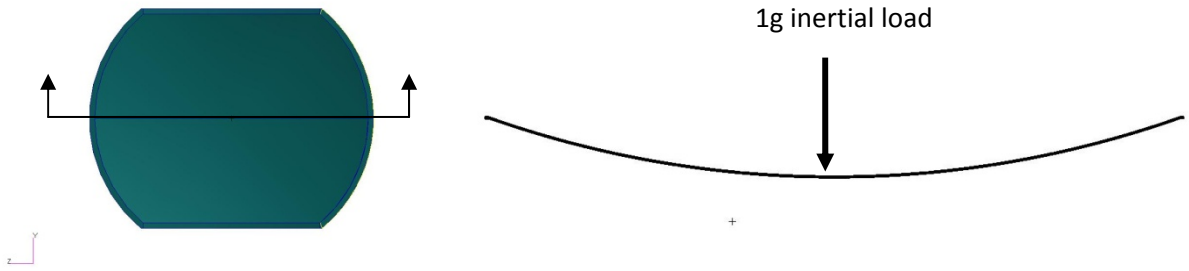


Figure 2 FEM Loading and location of cross section through the lens

A 1g inertial load was applied to the cross section FEM. The thickness was assumed to be 10mm, additional model runs using varied thicknesses were used, and 10mm yields the highest stress concentration factor. The stresses were evaluated at five cuts into the cross section, as shown in Figure 3.

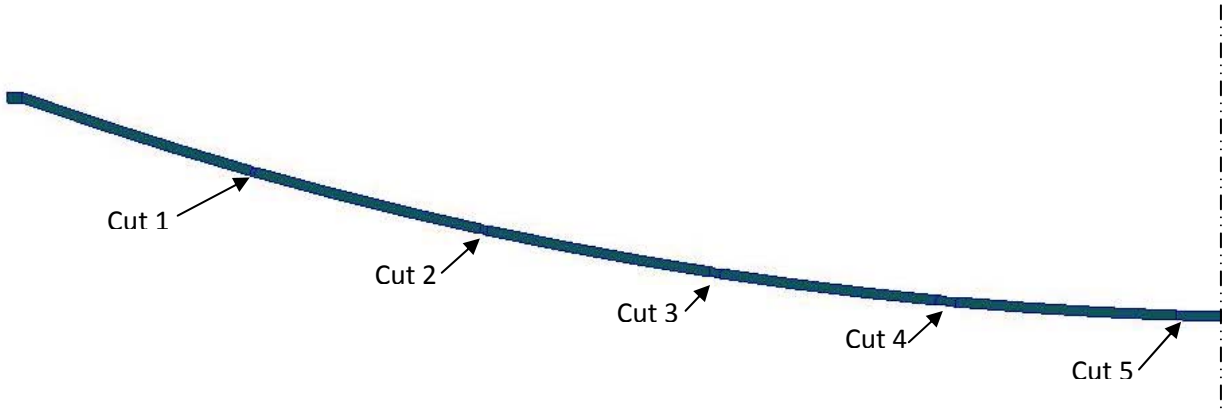


Figure 3 Location of the circumferential cuts

The most critical cut for stress concentration is Cut 1. A summary of the stresses and concentration factors is contained in Table 1.

Table 1 Summary of Peak Stresses for each cut location

	Stress with no cut	**Stress at cut, thickness = 40 mm**	**Stress at cut, thickness = 10 mm**	**Stress at cut, thickness = 5 mm**	**Max. Stress Concentration Factor, K**
Cut 1	5.62	19.3	20.0	20.0	**3.56**
Cut 2	6.00	18.2	20.4	20.4	3.40
Cut 3	5.17	15.1	15.8	15.8	3.06
Cut 4	5.32	13.7	14.3	14.3	2.69
Cut 5	5.95	10.6	11.7	11.7	1.97

The most critical cut is cut 1, the farthest cut from the center of the lens. The following figures illustrate the FEM mesh density used to determine the stress concentration factor. Conservatively, the radius in the corner of the cut was assumed to be zero, however the diameter of the tool used to make the cut has a diameter on the order of 1 to 4 microns.

The stress from the lens models will be increased by a factor of 3.56 to account for the notches.

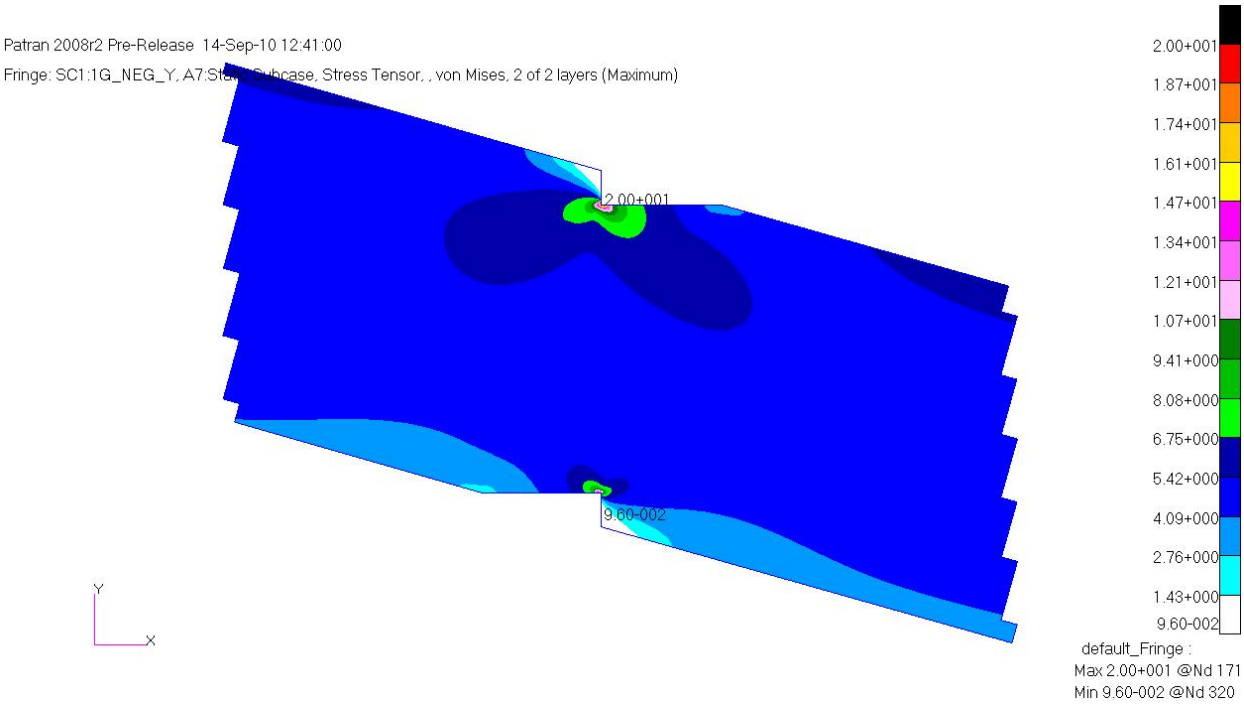


Figure 4 Stress plot at Cut 1 location, 1g in the negative Y direction

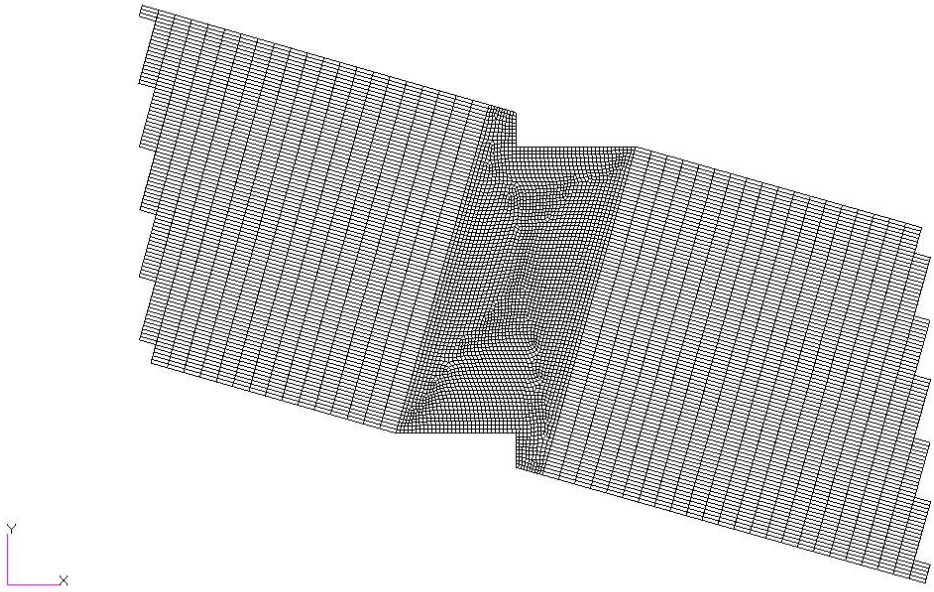
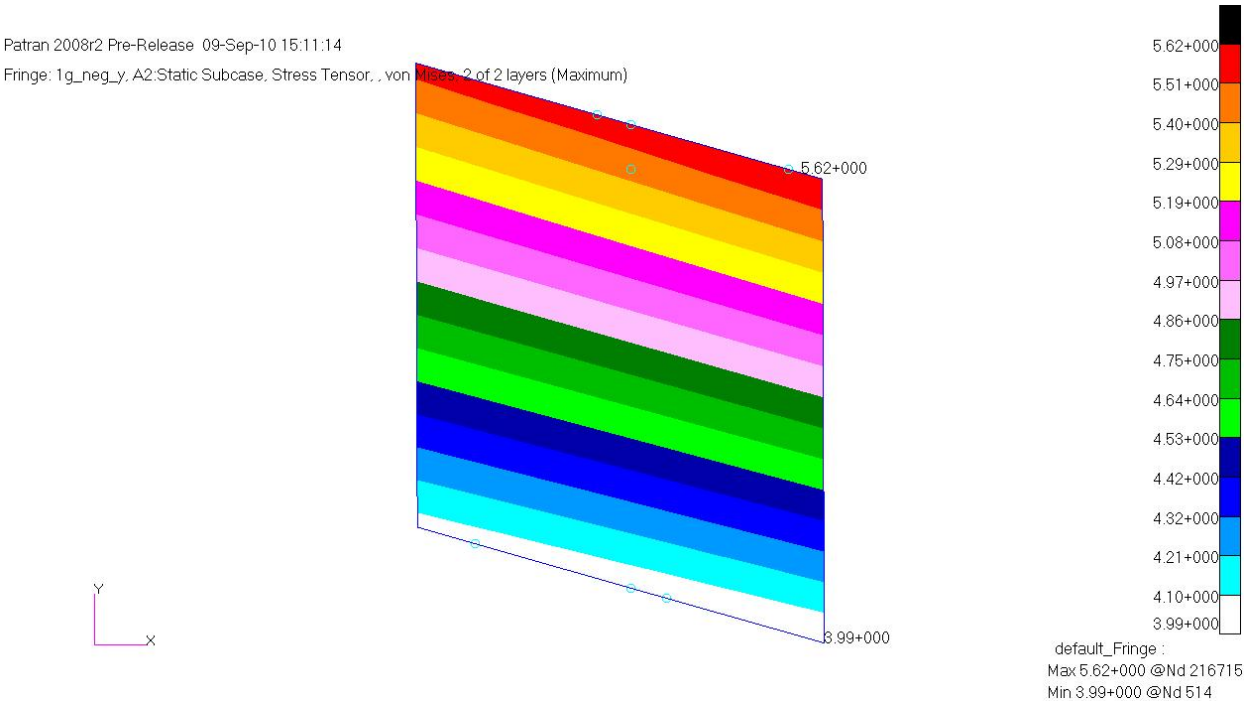
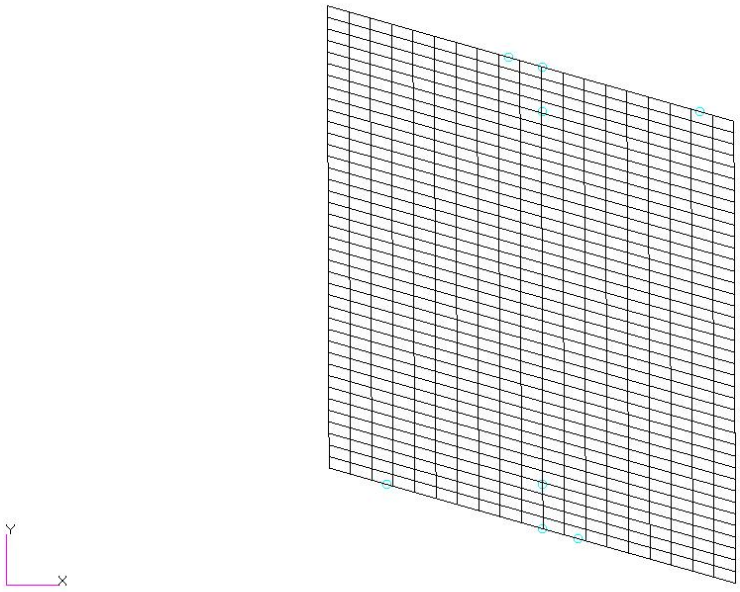


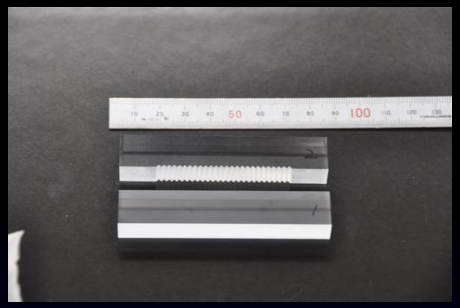
Figure 5 Mesh Density plot at Cut 1 location

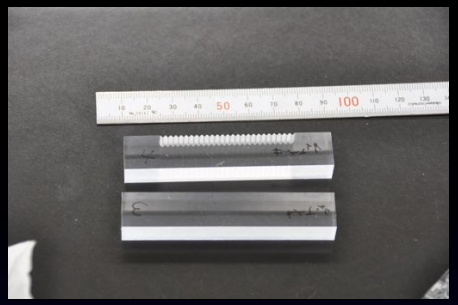


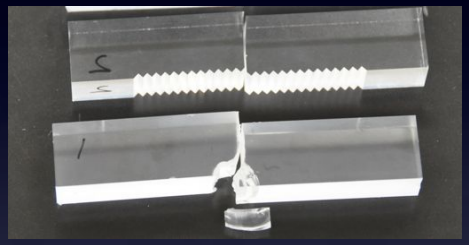


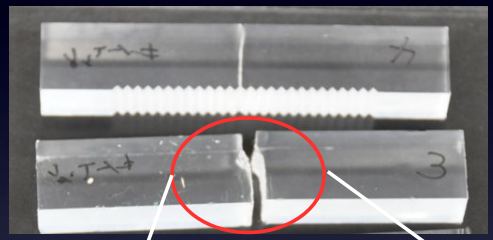
Material testing performed in Japan confirms the above results. The charts from the testing are included next. The Kt scaled from the test plot is 3.6 for PMMA. This is the Kt that will be used in the analysis.

PMMA-000　　CYTOP

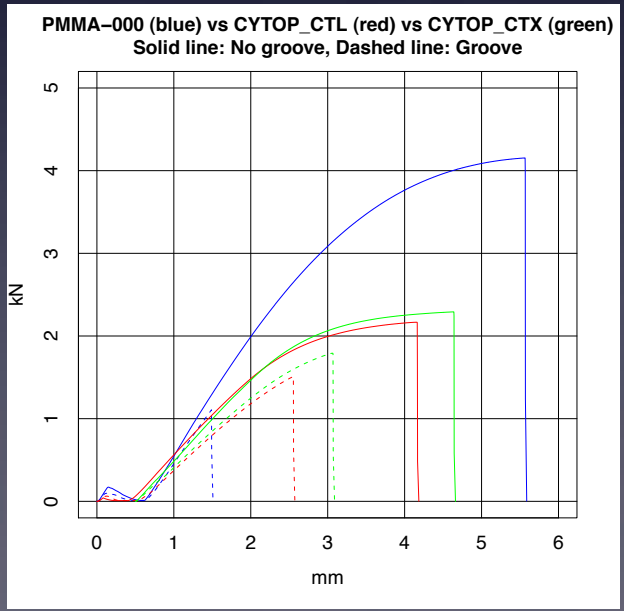


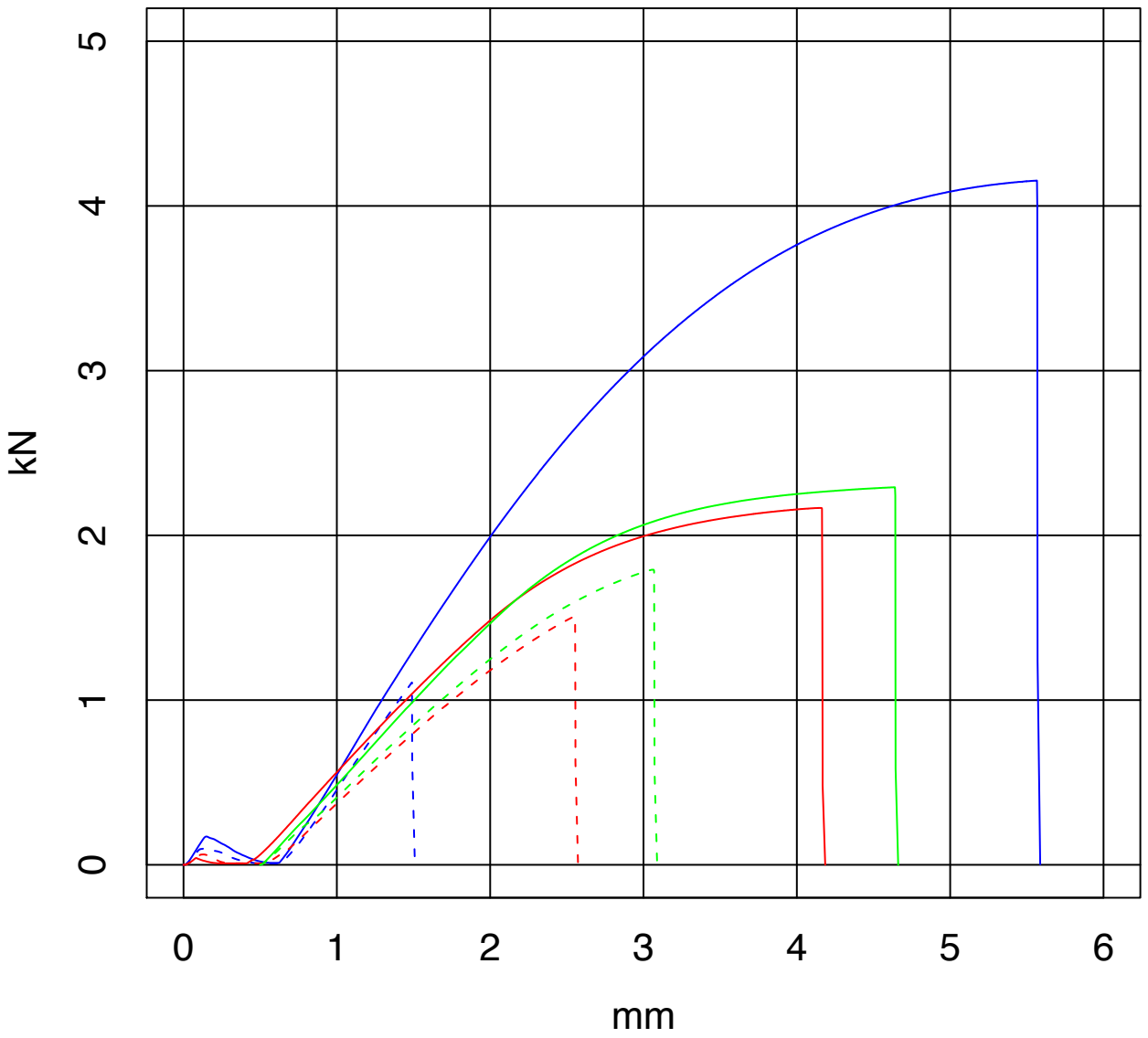


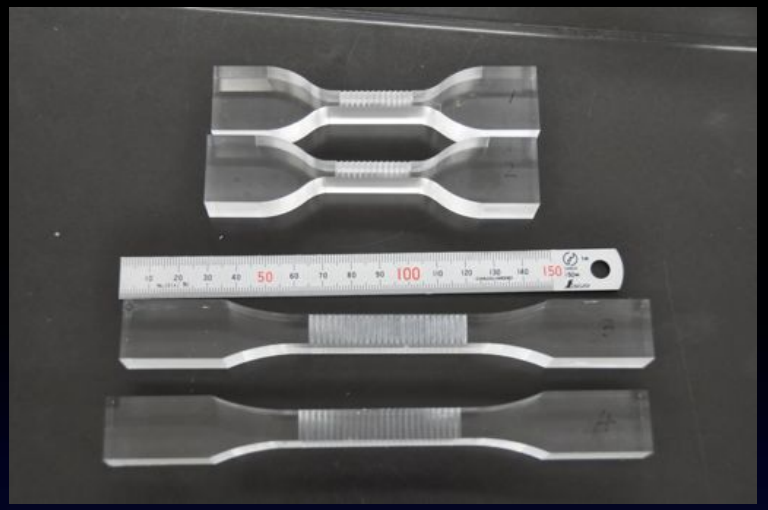


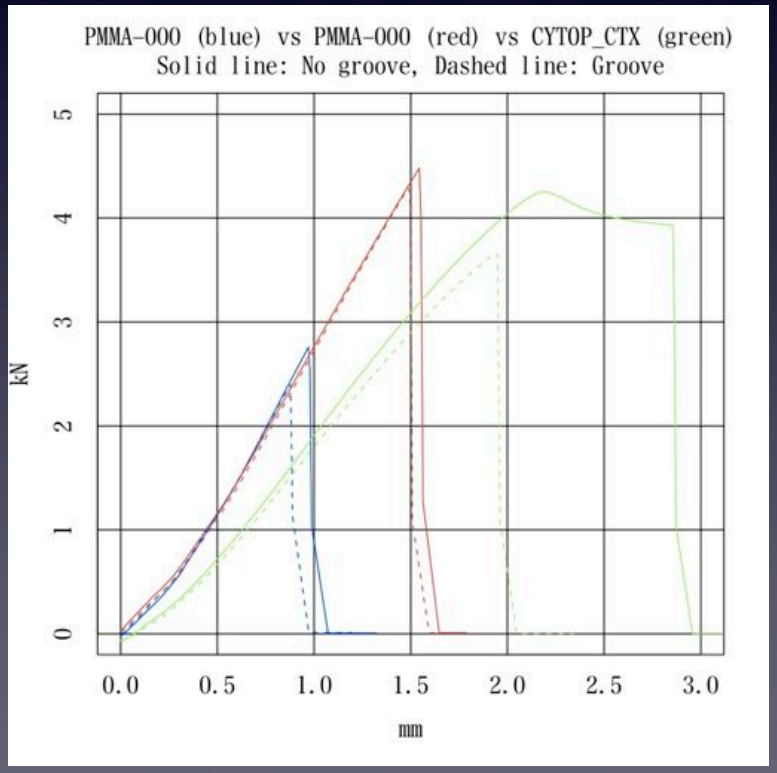


t15×w10
支点間距離 60mm

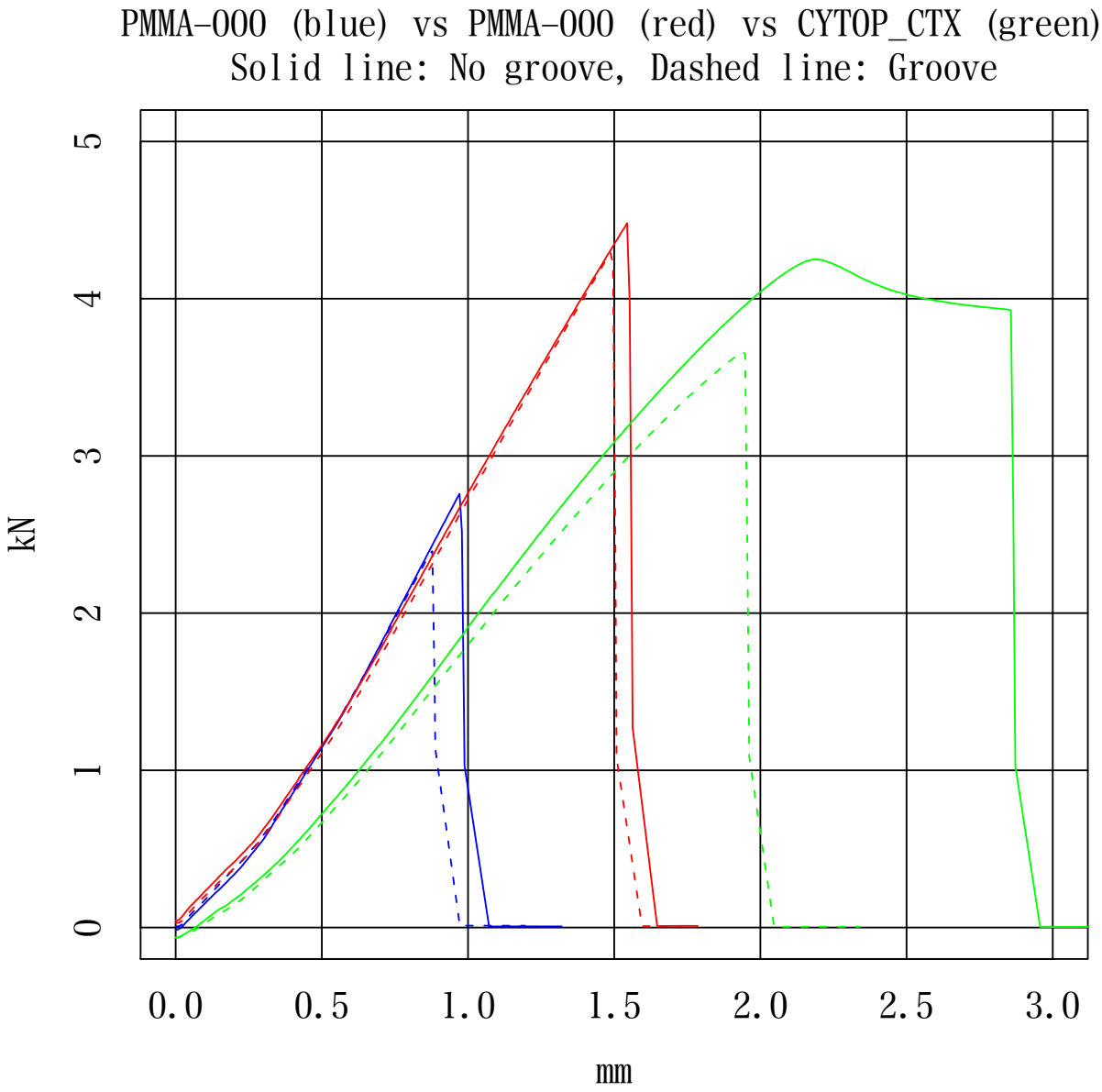



PMMA–000 (blue) vs CYTOP_CTL (red) vs CYTOP_CTX (green)
Solid line: No groove, Dashed line: Groove
kN
0
1
2
3
4
5
0
1
2
3
4
5
6
mm





サンプル1,2	t15×w6 つかみ具距離75mm
サンプル3.4	t15×w10 つかみ具距離110mm


PMMA-000 (blue) vs PMMA-000 (red) vs CYTOP_CTX (green)
Solid line: No groove, Dashed line: Groove
kN
0
1
2
3
4
5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
mm

Section 4 – One Piece Lens 3 in Frame 3

1. Finite Element Model

   A finite element model of a one piece lens 3 mounted in frame 3 was created. Plots of the model are shown below. The lens material is PMMA, the flexure material is Ti-6Al-4V, and the frame material is 6061-T6.

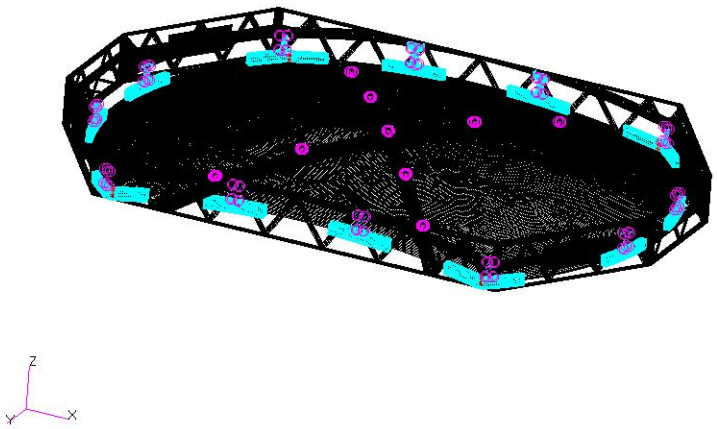


Figure 1: Lens 3 in Frame 3

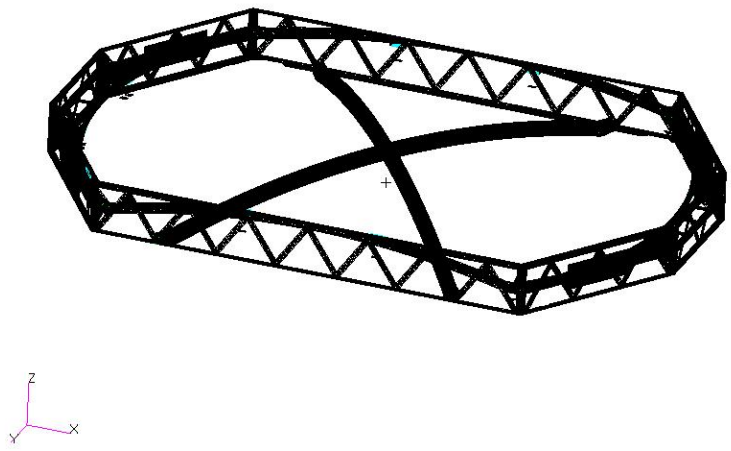


Figure 2: Frame 3

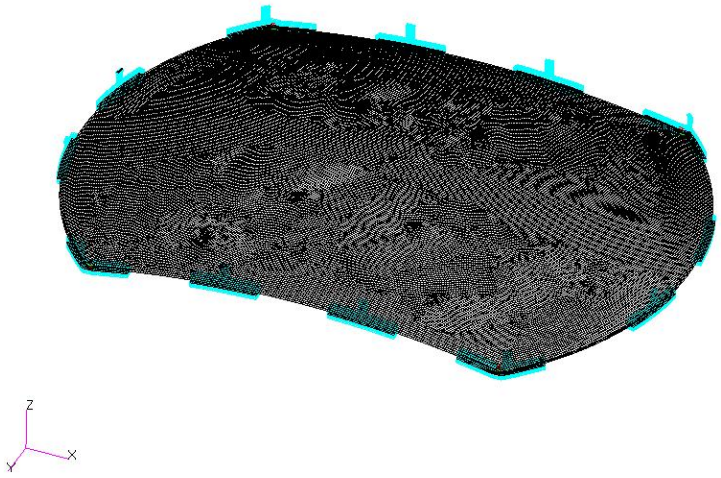


Figure 3: Lens 3 with Brackets and Flexures

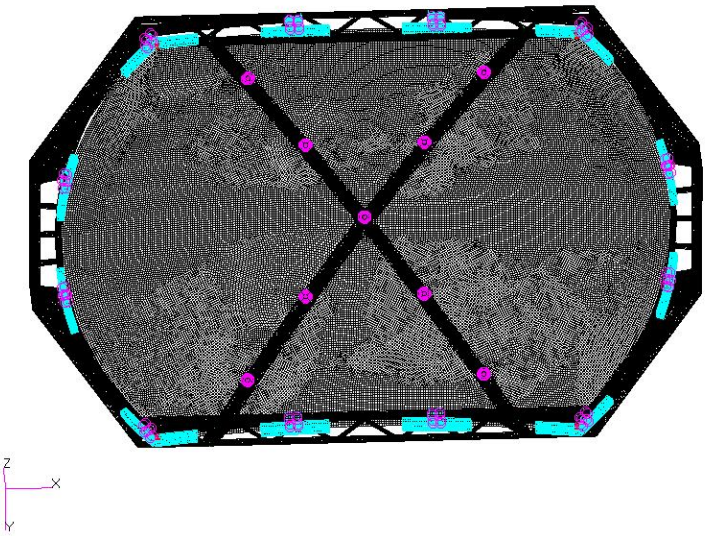


Figure 4: Lens 3 in Frame 3

2. Boundary Conditions

   The model was fixed in the three translation directions at the fasteners where the four masts attach to the frame. The boundary conditions are shown in Figure 5 and Figure 6.

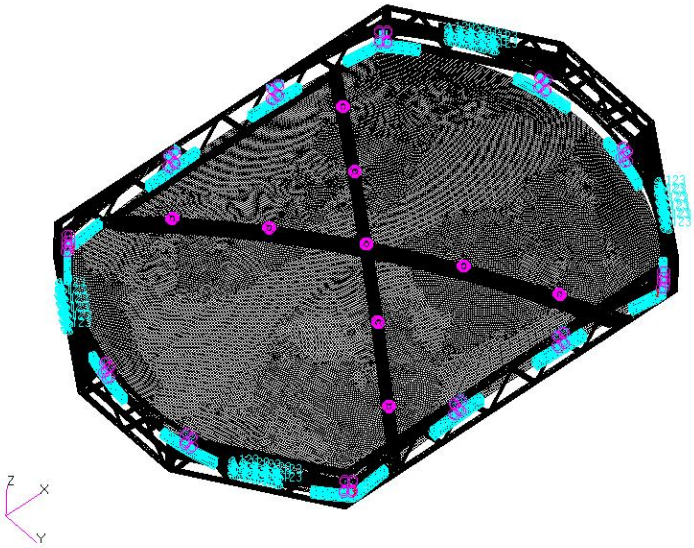


Figure 5: Frame Boundary Conditions

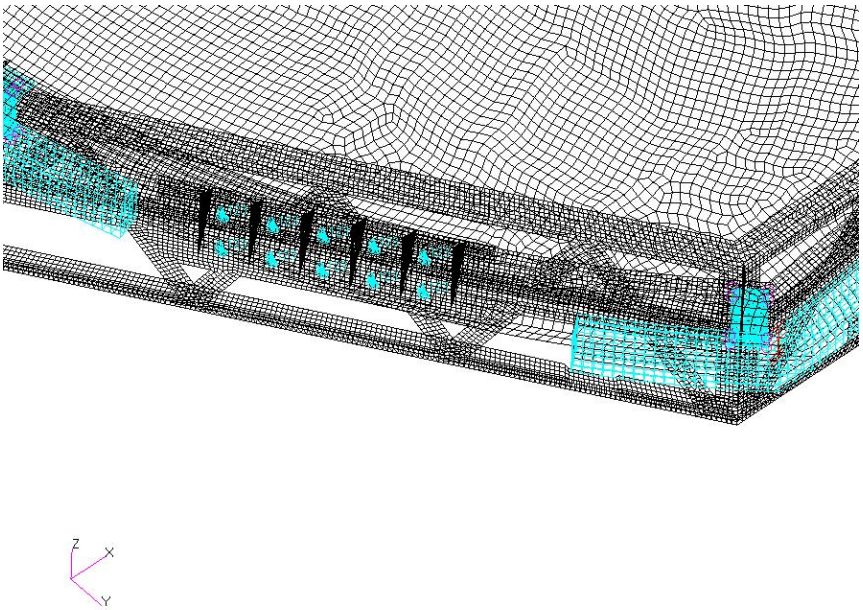
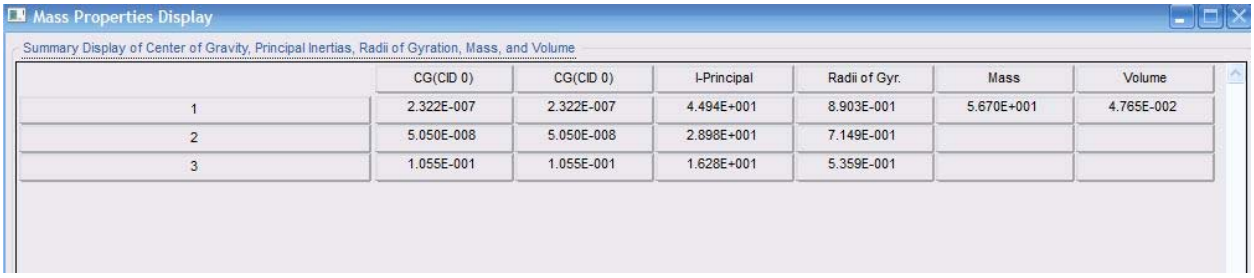


Figure 6: Close-up of Frame Boundary Conditions

3. Mass

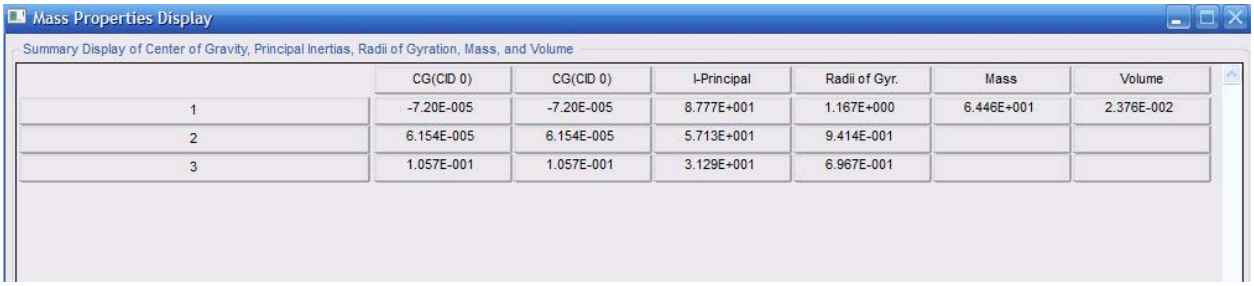
The mass of the lens in the model is 56.70 kg as shown below.


Mass Properties Display

Summary Display of Center of Gravity, Principal Inertias, Radii of Gyration, Mass, and Volume

	CG(CID 0)	CG(CID 0)	I-Principal	Radii of Gyr.	Mass	Volume
1	2.322E-007	2.322E-007	4.494E+001	8.903E-001	5.670E+001	4.765E-002
2	5.050E-008	5.050E-008	2.898E+001	7.149E-001		
3	1.055E-001	1.055E-001	1.628E+001	5.359E-001		

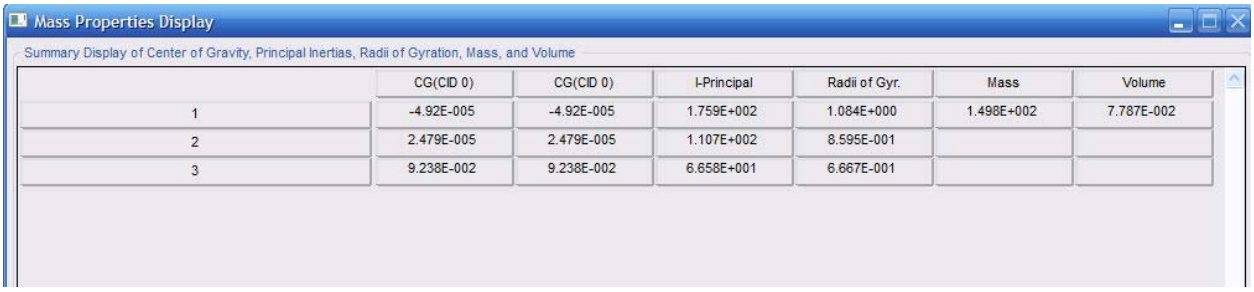
The mass of the frame in the model is 64.46 kg.


Mass Properties Display

Summary Display of Center of Gravity, Principal Inertias, Radii of Gyration, Mass, and Volume

	CG(CID 0)	CG(CID 0)	I-Principal	Radii of Gyr.	Mass	Volume
1	-7.20E-005	-7.20E-005	8.777E+001	1.167E+000	6.446E+001	2.376E-002
2	6.154E-005	6.154E-005	5.713E+001	9.414E-001		
3	1.057E-001	1.057E-001	3.129E+001	6.967E-001		

The total model mass is 149.8 kg.


Mass Properties Display

Summary Display of Center of Gravity, Principal Inertias, Radii of Gyration, Mass, and Volume

	CG(CID 0)	CG(CID 0)	I-Principal	Radii of Gyr.	Mass	Volume
1	-4.92E-005	-4.92E-005	1.759E+002	1.084E+000	1.498E+002	7.787E-002
2	2.479E-005	2.479E-005	1.107E+002	8.595E-001		
3	9.238E-002	9.238E-002	6.658E+001	6.667E-001		

The mass in the CAD model is 140.8 kg.

4. Frequency

The frequency of the model is determined first. An integrated frequency of 50 Hz is required, or coupled loads will have to be worked with the launch vehicle. A design goal of 25 Hz was established for a frame assembly. The frequency of this assembly meets that goal with a frequency of 25.6 Hz. As the mass of the lens is not insignificant, this is showing that most likely the integrated frequency will be below 50 Hz. It will be a project decision as to whether to work coupled loads with the launch vehicle or add additional structure that would block lens viewing to increase the frequency.

1 MSC.NASTRAN JOB CREATED ON 23-SEP-10 AT 11:55:43 MARCH 7, 2011 NX NASTRAN 9/17/09 PAGE 3941

0 SUBCASE 1

R E A L E I G E N V A L U E S

MODE NO.	EXTRACTION ORDER	EIGENVALUE	RADIANS	CYCLES	GENERALIZED MASS	GENERALIZED STIFFNESS
1	1	2.605217E+04	1.614068E+02	2.568870E+01	1.000000E+00	2.605217E+04
2	2	4.411616E+04	2.100385E+02	3.342866E+01	1.000000E+00	4.411616E+04
3	3	4.977357E+04	2.230999E+02	3.550745E+01	1.000000E+00	4.977357E+04
4	4	6.395646E+04	2.528961E+02	4.024967E+01	1.000000E+00	6.395646E+04
5	5	6.429892E+04	2.535723E+02	4.035729E+01	1.000000E+00	6.429892E+04
6	6	6.855954E+04	2.618388E+02	4.167294E+01	1.000000E+00	6.855954E+04
7	7	7.112159E+04	2.666863E+02	4.244444E+01	1.000000E+00	7.112159E+04
8	8	8.225696E+04	2.868047E+02	4.564639E+01	1.000000E+00	8.225696E+04
9	9	9.481731E+04	3.079242E+02	4.900766E+01	1.000000E+00	9.481731E+04
10	10	1.203245E+05	3.468783E+02	5.520739E+01	1.000000E+00	1.203245E+05

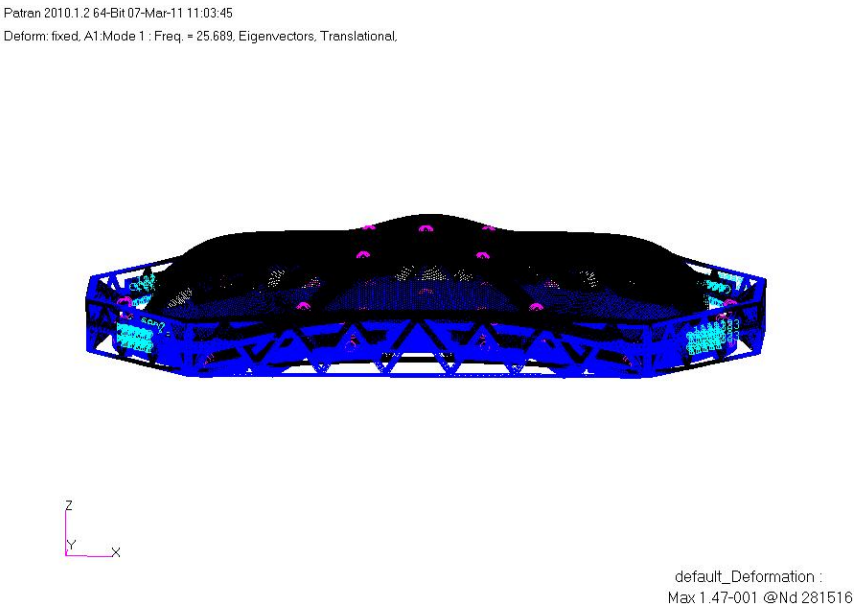


Figure 7: First Frequency Mode Shape

5. Launch Margins of Safety

The model was run using the calculated loads. The following load cases were used. Since the rotational accelerations need to be applied to the integrated model, the random accelerations were applied in all three axes simultaneously in this model to help account for the additional load in this partial model.

Load Case	Accel X (g's)	Accel Y (g's)	Accel Z (g's)
1	14.502	14.502	16.597
2	14.502	14.502	-16.597
3	14.502	-14.502	16.597
4	14.502	-14.502	-16.597

The maximum stress in the lens is shown in Figure 8 and the maximum deflection, in meters, in Figure 9. Using an untested factor of safety and the knockdown determined for the notch, the margin of safety is:

Stress, lens notched = 29.6 MPa, MS (ult) = -0.70

For the unnotched portion, the margin of safety is:

Stress, lens unnotched = 29.6 MPa, MS (ult) = +0.081

Another way to look at the stress plot is to plot the stress such that a positive margin is one color and a negative margin is a second color. This is shown in Figure 10 where the areas identified in red have a negative margin and those in blue have a positive margin using the notch knockdown. The peak stresses are occurring in the areas where the brackets are holding the lens, which may or may not be notched. Currently in the model, the lens is attached to the bracket as if the lens and bracket are one continuous solid. The next iteration of the model should update the attachments to be more realistic to determine if the peaking at the attachments is truly as high as predicted. These peaks also need to be compared with the notch locations to determine if any peaks coincide with a notch.

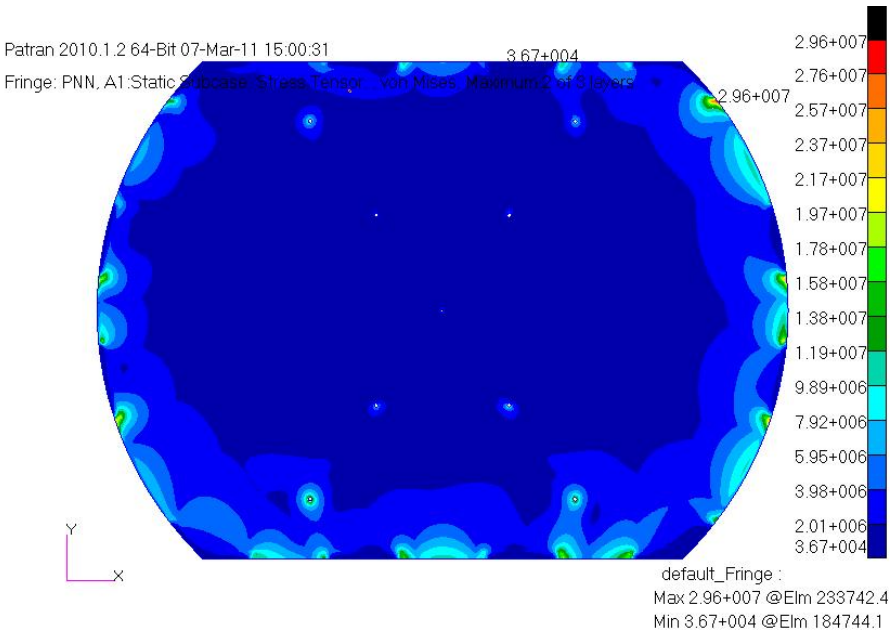


Figure 8: Maximum Stress in Lens 3

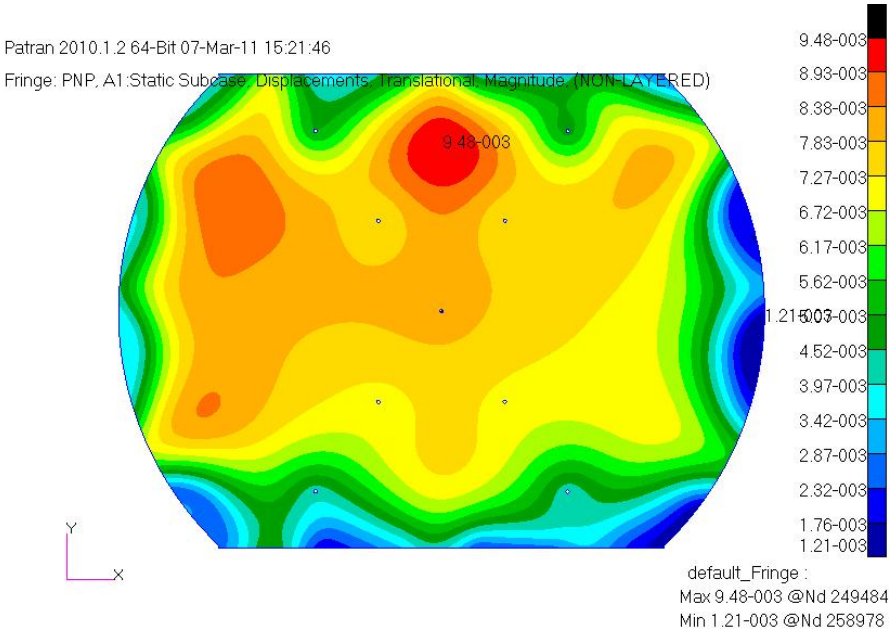


Figure 9: Maximum Deflection in Lens 3

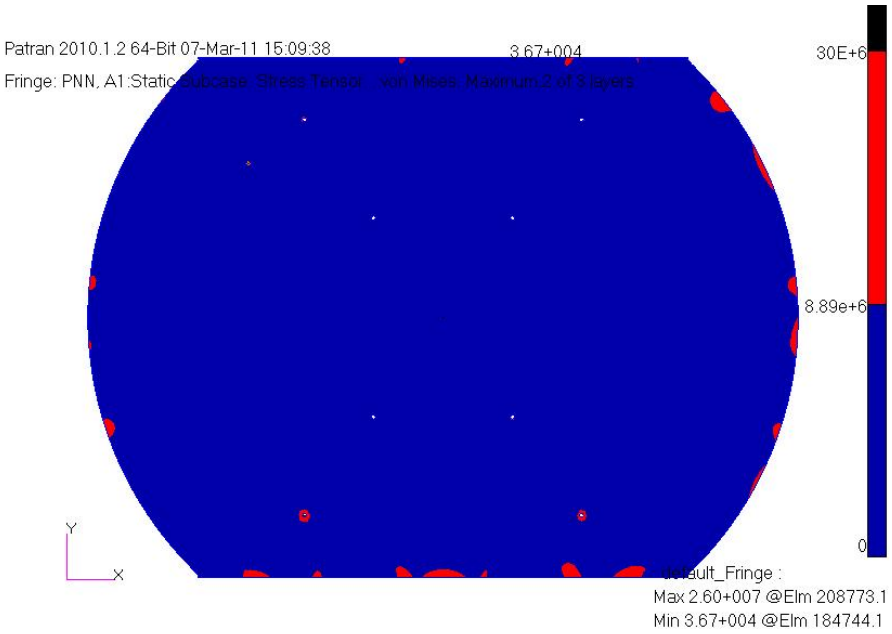


Figure 10 Negative Margin Plot of Lens 3

The maximum stress in the frame is shown in Figure 11 and Figure 12 with the maximum deflection, in meters, in Figure 13. Using untested factors of safety and ignoring local peaking at attachments, the margins of safety are:

Stress, frame at flexure = 250 MPa, MS (ult) = -0.42
MS (yld) = -0.22

Stress, frame everywhere else = 100 MPa, MS (ult) = +0.44
MS (yld) = +0.93

It's worth noting that the only places where the negative margin exists are at the flexure attachment to the frame. Everywhere else the margins of safety are positive. Therefore the thickness of the frame in the area of the flexure attachment needs to be thickened slightly to produce a positive margin. Other areas can be thinned to reduce mass if needed while keeping the frequency goal in mind.

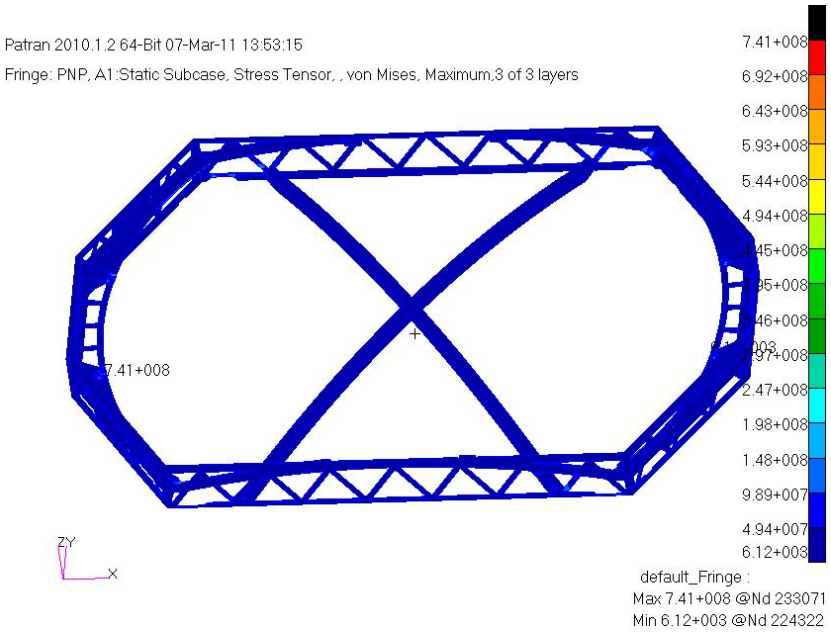


Figure 11: Maximum Stress in Frame 3

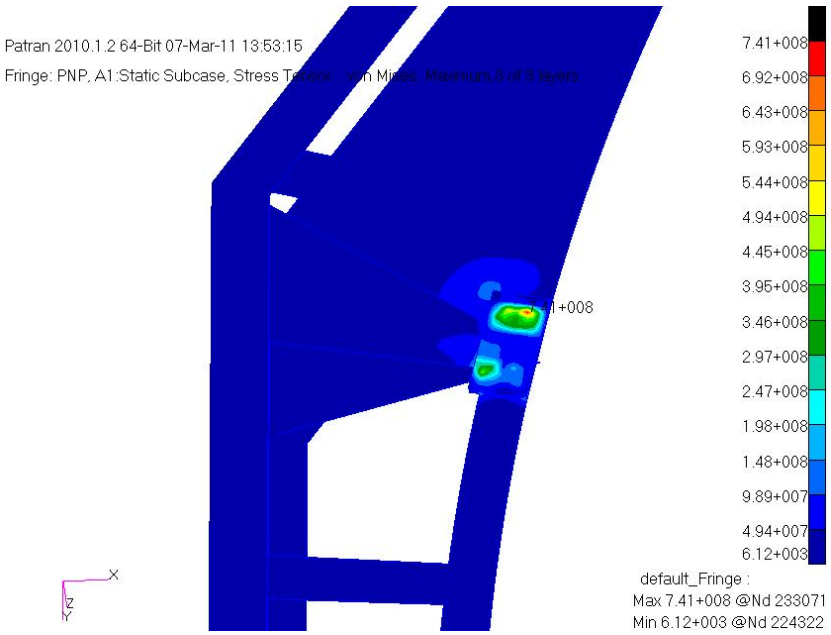


Figure 12: Close Up of Maximum Stress Area

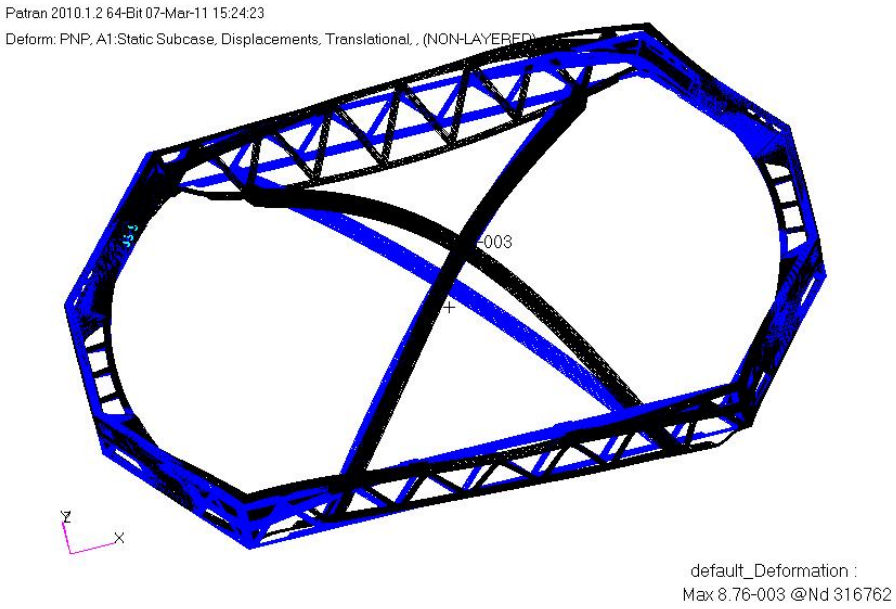


Figure 13: Maximum Deflection in Frame 3

The maximum stress in the flexure is shown in Figure 14. Using untested factors of safety and ignoring local peaking at attachments, the margins of safety are:

Stress, flexure at attachments = 2140 MPa, MS (ult) = -0.78
MS (yld) = -0.67

Stress, flexure everywhere else = 300 MPa, MS (ult) = +0.54
MS (yld) = +1.31

It's worth noting that the only places where the negative margin exists are at the flexure attachment to the frame and lens bracket. Everywhere else the margins of safety are positive. As the intent of this model was to assess the flexure in general and not necessarily the flexure attachment to the frame, the flanges of the flexure were not modeled. The next iteration of the model should include the flanges to more accurately model the flexure and determine if a margin issue exists or not. On the positive side, the flexure body is showing positive margins and will carry the required load.

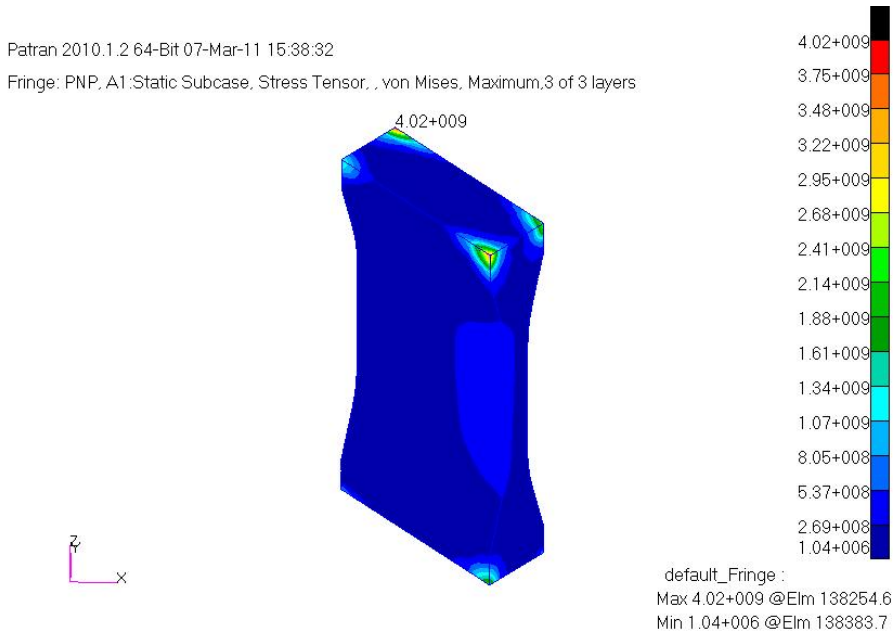


Figure 14: Maximum Stress in Flexure

6. Thermal Margins of Safety

The temperature of the model was varied between -20 C and + 40 C, with the assembly temperature of room temperature. The peak stress in the lens, flexure, and frame are shown in Figures 15, Figure 16, and Figure 17. Figure 18 and Figure 19 show the maximum displacement, in meters, of the assembly and lens only due to the change in temperature.

Using untested factors of safety, the margins of safety are:

Stress, lens notched = 25.3 MPa, MS (ult) = -0.64

Stress, lens unnotched = 25.3 MPa, MS (ult) = +0.26

Stress, frame at flexure = 350 MPa, MS (ult) = -0.58
MS (yld) = -0.44

Stress, frame everywhere else = 100 MPa, MS (ult) = +0.11
MS (yld) = +0.48

Stress, flexure at attachments = 1340 MPa, MS (ult) = -0.65
MS (yld) = -0.48

Stress, flexure everywhere else = 400 MPa, MS (ult) = +0.15
MS (yld) = +0.73

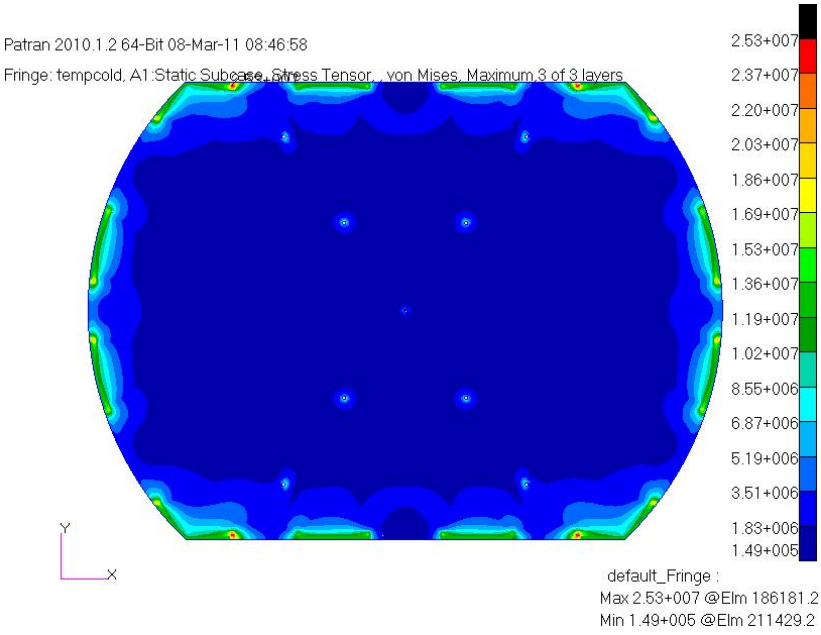


Figure 15: Maximum Stress in Lens 3 due to Thermal

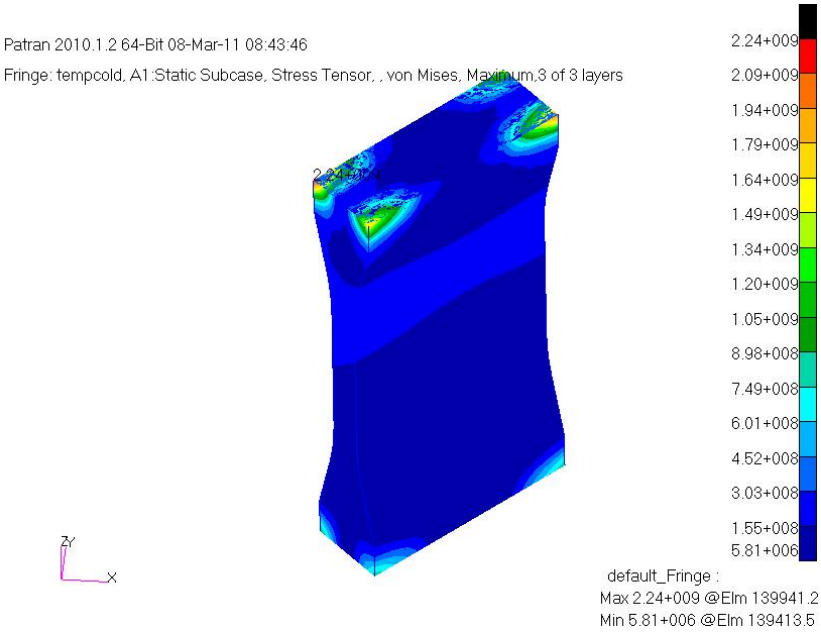


Figure 16: Maximum Stress in Flexure due to Thermal

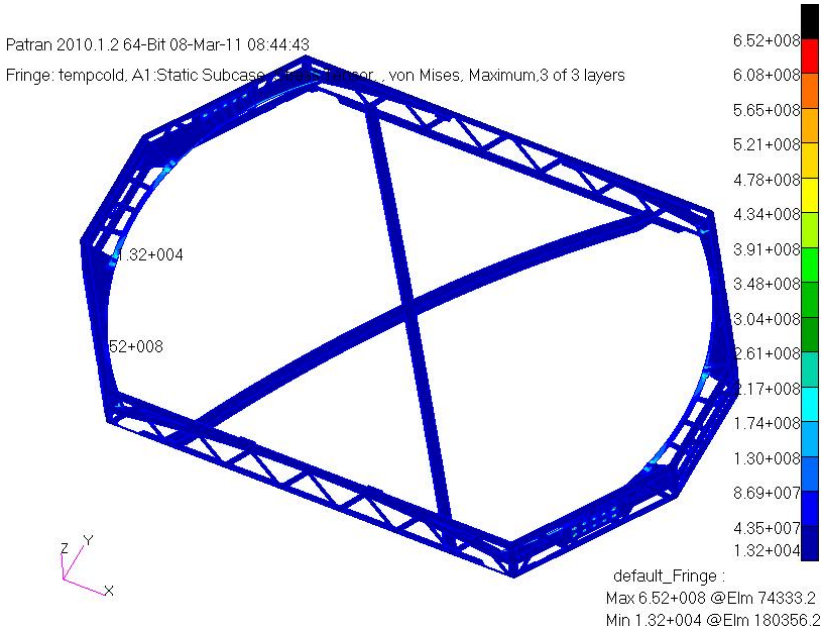


Figure 17: Maximum Stress in Frame 3 due to Thermal

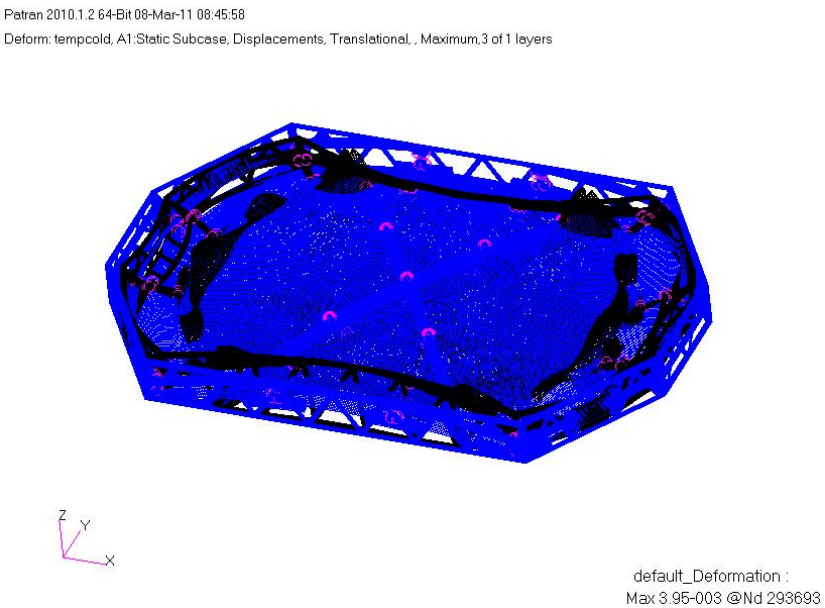


Figure 18: Maximum Deflection due to Thermal

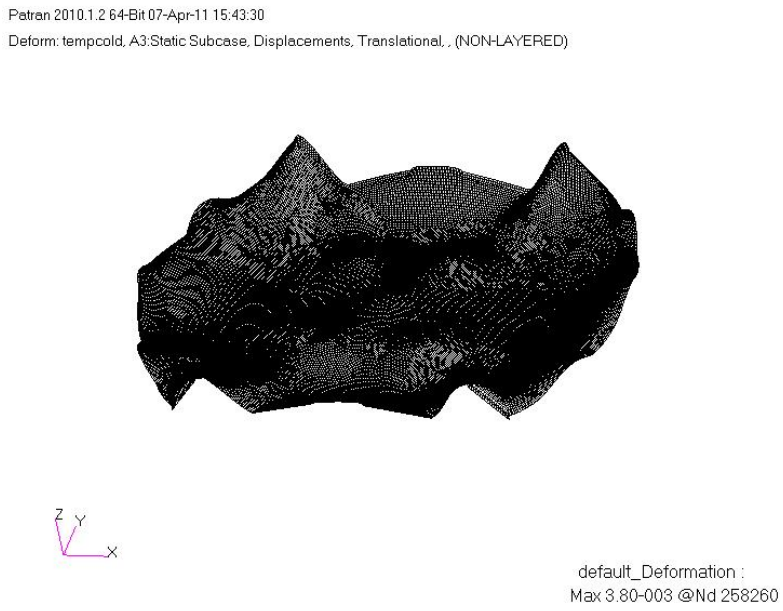


Figure 19: Maximum Deflection of Lens due to Thermal

The analysis shows the same problem areas as in the launch acceleration load cases. The same design changes and lens notch location information will also improve these margins. Also, the fixed constraint does not take into account that the mast attachment allows expanding or contracting with a temperature change. The effect of the mast on the frame needs to be considered in future iterations and will reduce the peak stresses in the frame shown in this analysis.

7. Model Checks

Time did not permit a complete quality check of the model. The following checks were performed on the model.

A free-free run was performed to verify the first six frequencies are zero and the seventh frequency is significantly higher. The results are shown below.

1 MSC.NASTRAN JOB CREATED ON 23-SEP-10 AT 11:55:43 MARCH 7, 2011 NX NASTRAN 9/17/09 PAGE 3941

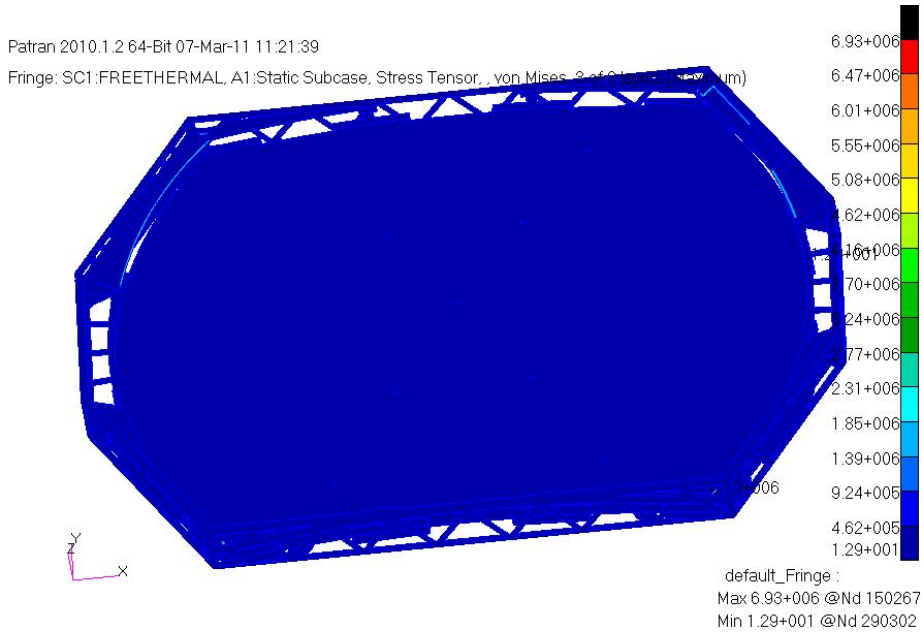
0 SUBCASE 1

R E A L E I G E N V A L U E S

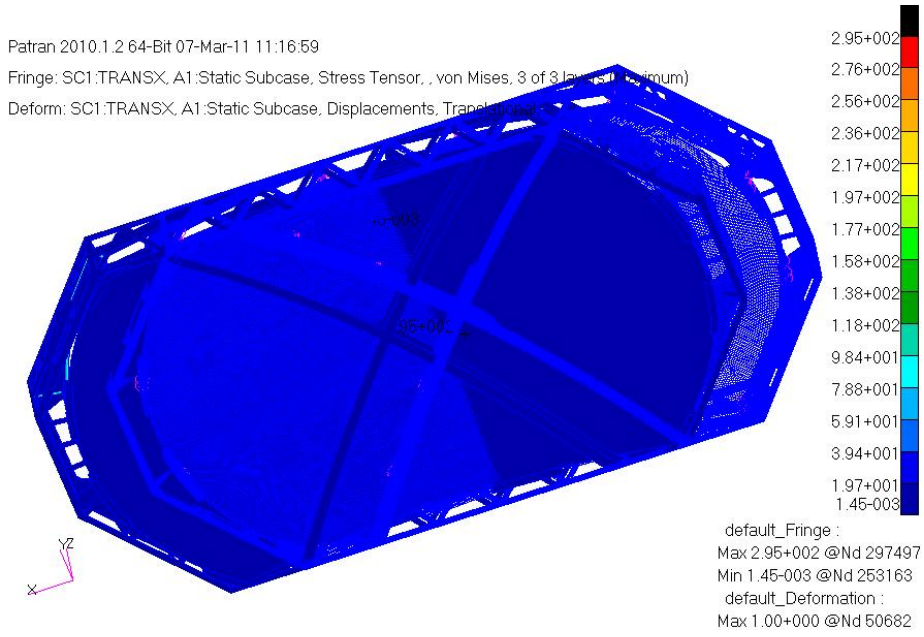
MODE NO.	EXTRACTION ORDER	EIGENVALUE	RADIANS	CYCLES	GENERALIZED MASS	GENERALIZED STIFFNESS
1	1	-4.493401E-06	2.119764E-03	3.373710E-04	1.000000E+00	-4.493401E-06
2	2	-3.340046E-06	1.827579E-03	2.908683E-04	1.000000E+00	-3.340046E-06
3	3	-2.273799E-06	1.507912E-03	2.399917E-04	1.000000E+00	-2.273799E-06
4	4	6.459015E-07	8.036800E-04	1.279096E-04	1.000000E+00	6.459015E-07
5	5	8.423991E-07	9.178231E-04	1.460761E-04	1.000000E+00	8.423991E-07
6	6	2.719050E-06	1.648954E-03	2.624392E-04	1.000000E+00	2.719050E-06
7	7	7.788813E+03	8.825425E+01	1.404610E+01	1.000000E+00	7.788813E+03
8	8	1.145674E+04	1.070362E+02	1.703533E+01	1.000000E+00	1.145674E+04
9	9	2.225254E+04	1.491729E+02	2.374160E+01	1.000000E+00	2.225254E+04
10	10	5.296067E+04	2.301319E+02	3.662662E+01	1.000000E+00	5.296067E+04

A free expansion check was performed to verify the stress is close to zero. There is a peak stress occurring at some of the frame intersections. The peak stress of 6.93E+6 Pa or 1005 psi is a little

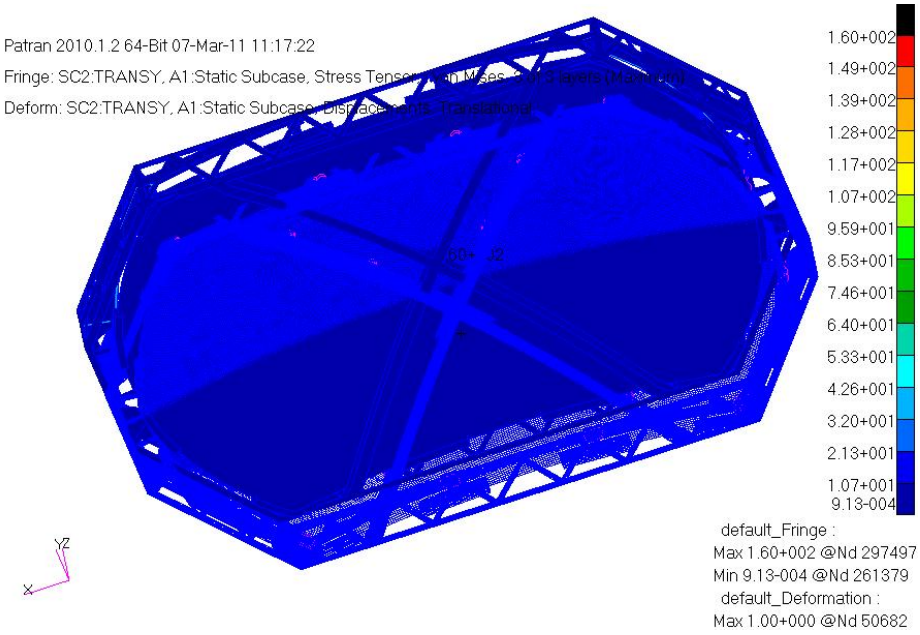
higher than desired for this check. However, time did not permit the mesh to be regenerated. Further iterations of the model need to modify the mesh in those areas.



An enforced displacement check was performed to verify the stress is close to zero. The results are similar to the free expansion check results. The max stress from the six load cases is around 2.51e+7 Pa or 3640 psi. Further iterations of the model need to refine the mesh in the affected areas to reduce the stress.

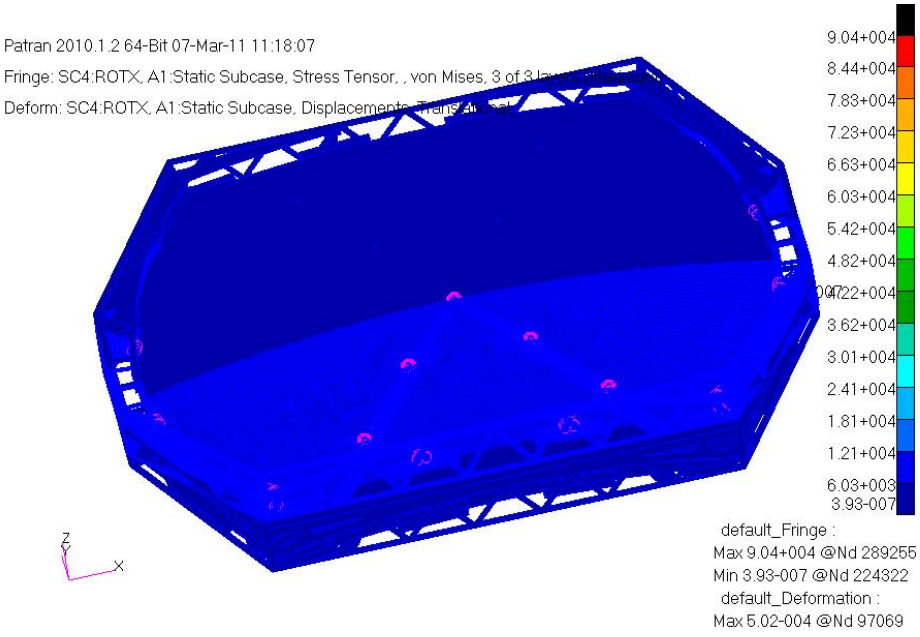


Enforced Displacement in X Translation

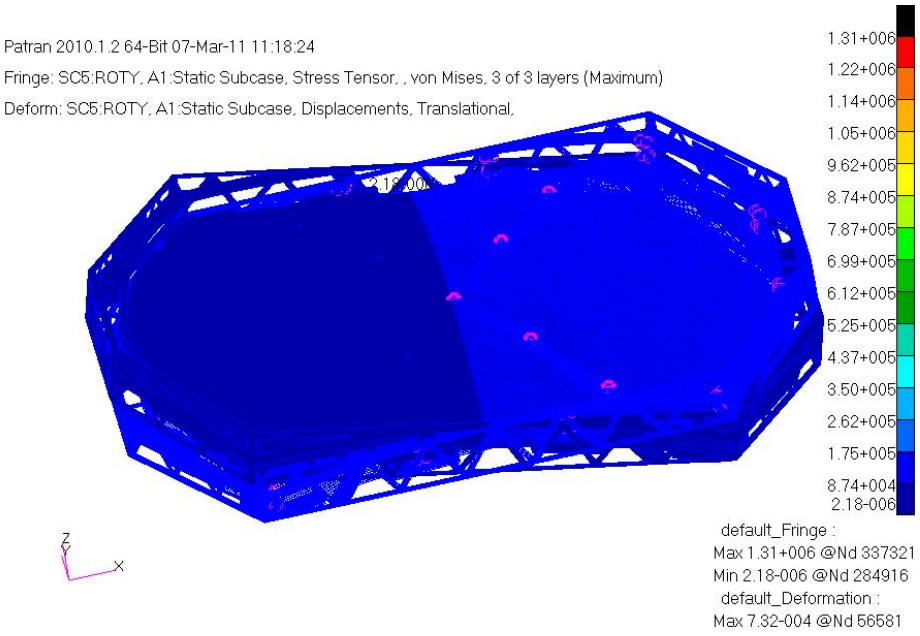


Enforced Displacement in Y Translation

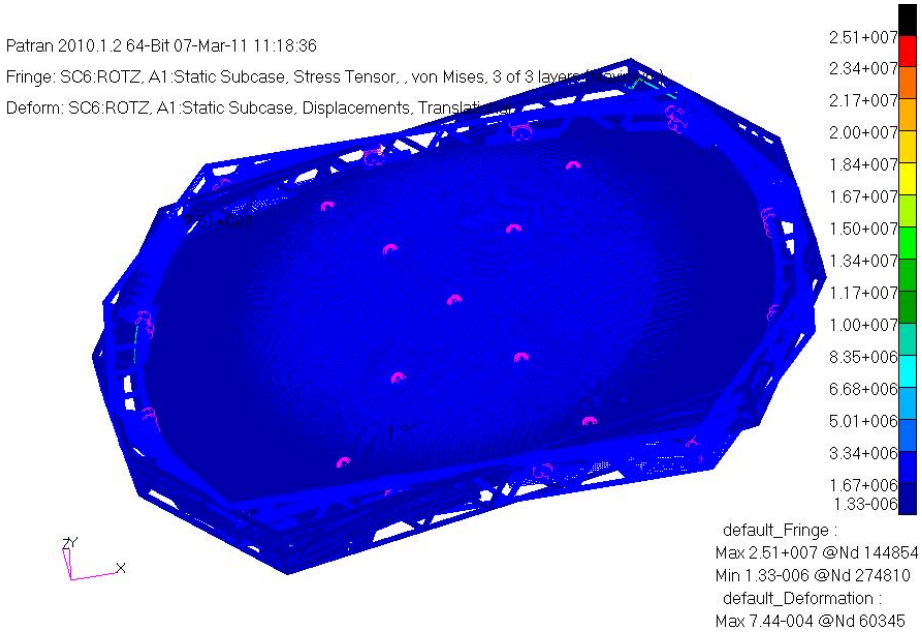
Enforced Displacement in Z Translation



Enforced Displacement in X Rotation

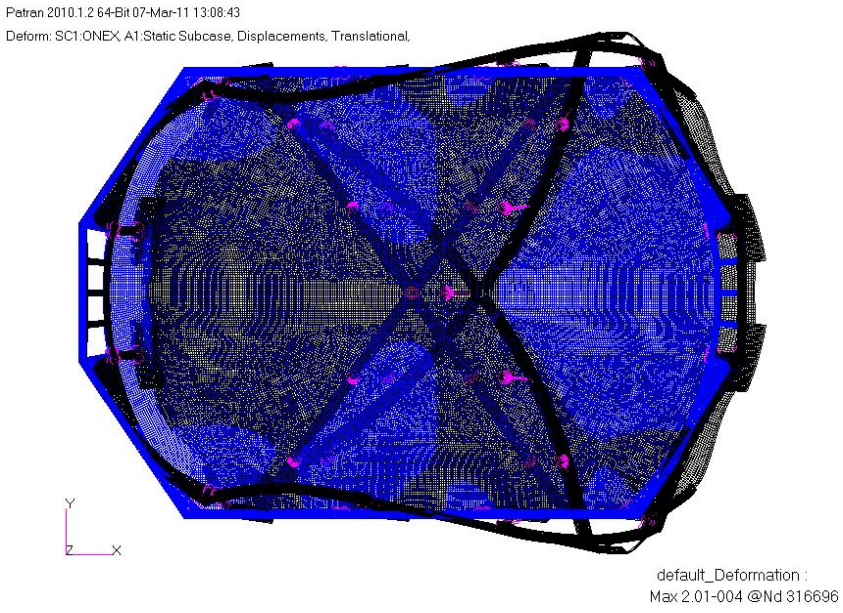


Enforced Displacement in Y Rotation

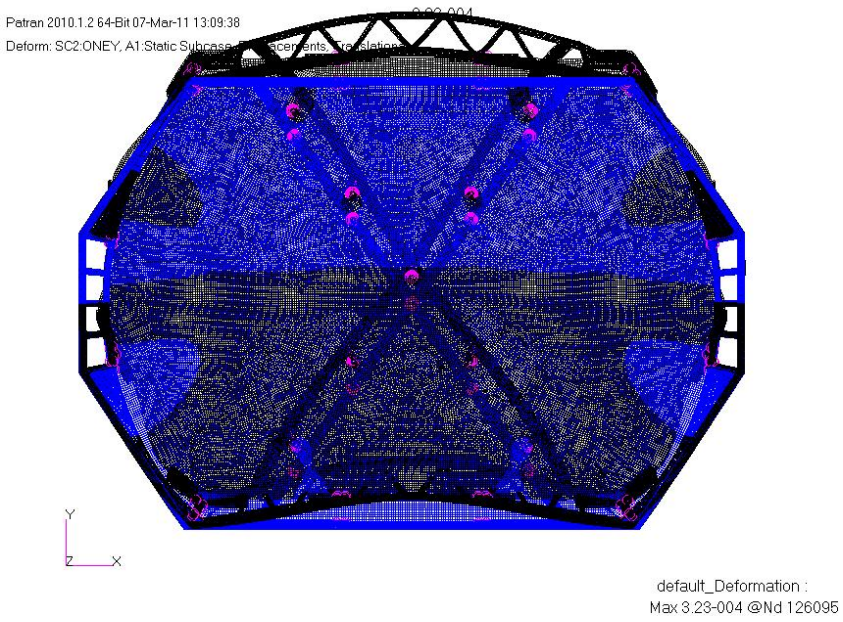


Enforced Displacement in Z Rotation

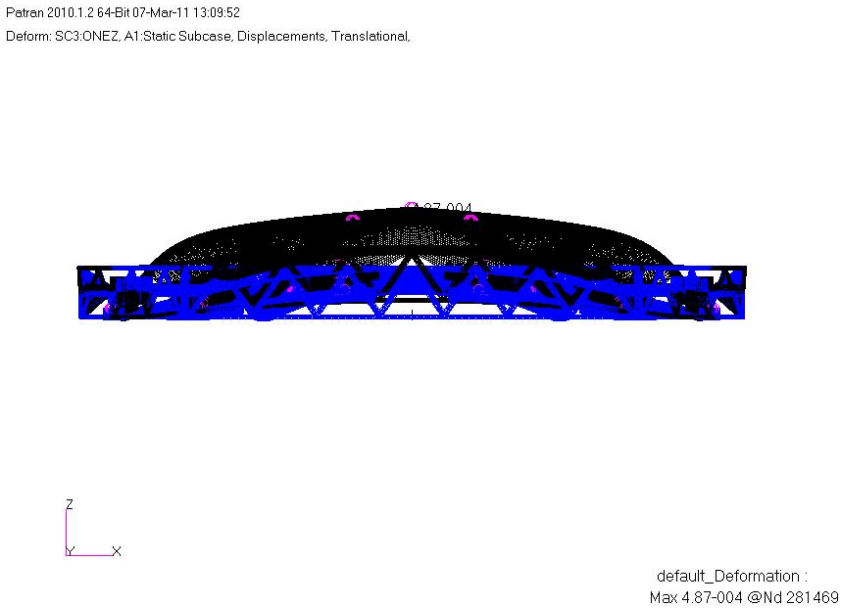
The model was run with one g applied in each axis at a time to verify the model behaved properly. The displacement plots from the three load cases are shown below.



One G in X Direction



One G in Y Direction



One G in Z Direction

The residual vector error for the stress runs is verified to be less than 10e-6. The following are the errors from the Nastran runs.

Epsilon from Strength Analysis

```
1    MSC.NASTRAN JOB CREATED ON 23-SEP-10 AT 11:55:43                        MARCH    7, 2011  NX NASTRAN  9/17/09   PAGE  3944

0                                                                                                                  SUBCASE 1
 *** USER INFORMATION MESSAGE 5293 (SSG3A)
     FOR DATA BLOCK KLL
     LOAD SEQ. NO.              EPSILON              EXTERNAL WORK      EPSILONS LARGER THAN 0.001 ARE FLAGGED WITH ASTERISKS
                 1         -1.9767946E-11          7.0760788E+01
                 2         -2.1906112E-11          7.0732162E+01
                 3         -1.9330039E-11          7.0789848E+01
                 4         -2.9354449E-11          7.0798386E+01
```

Epsilon from Thermal Cold Analysis

```
1    MSC.NASTRAN JOB CREATED ON 23-SEP-10 AT 11:55:43                        MARCH    8, 2011  NX NASTRAN  9/17/09   PAGE  3943

0                                                                                                                  SUBCASE 1
 *** USER INFORMATION MESSAGE 5293 (SSG3A)
     FOR DATA BLOCK KLL
     LOAD SEQ. NO.              EPSILON              EXTERNAL WORK      EPSILONS LARGER THAN 0.001 ARE FLAGGED WITH ASTERISKS
                 1         -1.2497027E-15          4.3727480E+03
```

Epsilon from Thermal Hot Analysis

```
1    MSC.NASTRAN JOB CREATED ON 23-SEP-10 AT 11:55:43                        MARCH    8, 2011  NX NASTRAN  9/17/09   PAGE  3943

0                                                                                                                  SUBCASE 1
 *** USER INFORMATION MESSAGE 5293 (SSG3A)
     FOR DATA BLOCK KLL
     LOAD SEQ. NO.              EPSILON              EXTERNAL WORK      EPSILONS LARGER THAN 0.001 ARE FLAGGED WITH ASTERISKS
                 1          2.6751015E-14          9.3906134E+02
```

Epsilon from One G Analysis

```
1    MSC.NASTRAN JOB CREATED ON 23-SEP-10 AT 11:55:43                        MARCH    7, 2011  NX NASTRAN  9/17/09   PAGE  3942

0                                                                                                                  SUBCASE 1
 *** USER INFORMATION MESSAGE 5293 (SSG3A)
     FOR DATA BLOCK KLL
     LOAD SEQ. NO.              EPSILON              EXTERNAL WORK      EPSILONS LARGER THAN 0.001 ARE FLAGGED WITH ASTERISKS
                 1         -2.6010593E-12          6.0427312E-02
                 2         -1.2751002E-11          7.5651579E-02
                 3         -2.8021951E-11          1.5302314E-01
```

Epsilon from Enforced Displacement Analysis

```
0                                                                                                                    SUBCASE 1
 *** USER INFORMATION MESSAGE 5293 (SSG3A)
    FOR DATA BLOCK KLL
    LOAD SEQ. NO.              EPSILON              EXTERNAL WORK      EPSILONS LARGER THAN 0.001 ARE FLAGGED WITH ASTERISKS
               1         -8.4876970E-14          7.7614874E+08
1    MSC.NASTRAN JOB CREATED ON 23-SEP-10 AT 11:55:43                          MARCH   7, 2011  NX NASTRAN  9/17/09   PAGE 23593

0                                                                                                                    SUBCASE 2
 *** USER INFORMATION MESSAGE 5293 (SSG3A)
    FOR DATA BLOCK KLL
    LOAD SEQ. NO.              EPSILON              EXTERNAL WORK      EPSILONS LARGER THAN 0.001 ARE FLAGGED WITH ASTERISKS
               2         -3.0609053E-14          1.0194179E+09
1    MSC.NASTRAN JOB CREATED ON 23-SEP-10 AT 11:55:43                          MARCH   7, 2011  NX NASTRAN  9/17/09   PAGE 23594

0                                                                                                                    SUBCASE 3
 *** USER INFORMATION MESSAGE 5293 (SSG3A)
    FOR DATA BLOCK KLL
    LOAD SEQ. NO.              EPSILON              EXTERNAL WORK      EPSILONS LARGER THAN 0.001 ARE FLAGGED WITH ASTERISKS
               3         -7.3511909E-14          1.2471291E+09
1    MSC.NASTRAN JOB CREATED ON 23-SEP-10 AT 11:55:43                          MARCH   7, 2011  NX NASTRAN  9/17/09   PAGE 23595

0                                                                                                                    SUBCASE 4
 *** USER INFORMATION MESSAGE 5293 (SSG3A)
    FOR DATA BLOCK KLL
    LOAD SEQ. NO.              EPSILON              EXTERNAL WORK      EPSILONS LARGER THAN 0.001 ARE FLAGGED WITH ASTERISKS
               4         -5.9348593E-09          9.9381583E-04
1    MSC.NASTRAN JOB CREATED ON 23-SEP-10 AT 11:55:43                          MARCH   7, 2011  NX NASTRAN  9/17/09   PAGE 23596

0                                                                                                                    SUBCASE 5
 *** USER INFORMATION MESSAGE 5293 (SSG3A)
    FOR DATA BLOCK KLL
    LOAD SEQ. NO.              EPSILON              EXTERNAL WORK      EPSILONS LARGER THAN 0.001 ARE FLAGGED WITH ASTERISKS
               5         -2.8674620E-09          2.0265663E-03
1    MSC.NASTRAN JOB CREATED ON 23-SEP-10 AT 11:55:43                          MARCH   7, 2011  NX NASTRAN  9/17/09   PAGE 23597

0                                                                                                                    SUBCASE 6
 *** USER INFORMATION MESSAGE 5293 (SSG3A)
    FOR DATA BLOCK KLL
    LOAD SEQ. NO.              EPSILON              EXTERNAL WORK      EPSILONS LARGER THAN 0.001 ARE FLAGGED WITH ASTERISKS
               6         -7.1195654E-09          3.0328359E-03
```

Epsilon from Free Thermal Expansion Analysis

```
1    MSC.NASTRAN JOB CREATED ON 23-SEP-10 AT 11:55:43                          MARCH   7, 2011  NX NASTRAN  9/17/09   PAGE  3943

0                                                                                                                    SUBCASE 1
 *** USER INFORMATION MESSAGE 5293 (SSG3A)
    FOR DATA BLOCK KLL
    LOAD SEQ. NO.              EPSILON              EXTERNAL WORK      EPSILONS LARGER THAN 0.001 ARE FLAGGED WITH ASTERISKS
               1         -1.6542099E-14          4.9867199E+01
```

Margin of Safety Calculations - Accelerations

Lens - Notched

$$MS_{lensnotched_a} := \frac{64 \cdot MPa}{2 \cdot 3.6 \cdot 29.6 \cdot MPa} - 1 \qquad MS_{lensnotched_a} = -0.7$$

Lens - Unnotched

$$MS_{lens_a} := \frac{64 \cdot MPa}{2 \cdot 1.0 \cdot 29.6 \cdot MPa} - 1 \qquad MS_{lens_a} = 0.081$$

Frame At Flexure

$$MS_{frameflexurelocalult_a} := \frac{289.58 \cdot MPa}{2 \cdot 250 \cdot MPa} - 1 \qquad MS_{frameflexurelocalult_a} = -0.421$$

$$MS_{frameflexurelocalyld_a} := \frac{241.317 \cdot MPa}{1.25 \cdot 250 \cdot MPa} - 1 \qquad MS_{frameflexurelocalyld_a} = -0.228$$

Frame Everywhere Else

$$MS_{frameflexureult_a} := \frac{289.58 \cdot MPa}{2 \cdot 100 \cdot MPa} - 1 \qquad MS_{frameflexureult_a} = 0.448$$

$$MS_{frameflexureyld_a} := \frac{241.317 \cdot MPa}{1.25 \cdot 100 \cdot MPa} - 1 \qquad MS_{frameflexureyld_a} = 0.931$$

Flexure at Attachments

$$MS_{flexurelocalult_a} := \frac{923.89 \cdot MPa}{2 \cdot 2140 \cdot MPa} - 1 \qquad MS_{flexurelocalult_a} = -0.784$$

$$MS_{flexurelocalyld_a} := \frac{868.73 \cdot MPa}{1.25 \cdot 2140 \cdot MPa} - 1 \qquad MS_{flexurelocalyld_a} = -0.675$$

Flexure Everywhere Else

$$MS_{flexureult_a} := \frac{923.89 \cdot MPa}{2 \cdot 300 \cdot MPa} - 1 \qquad MS_{flexureult_a} = 0.54$$

$$MS_{flexureyld_a} := \frac{868.73 \cdot MPa}{1.25 \cdot 300 \cdot MPa} - 1 \qquad MS_{flexureyld_a} = 1.317$$

Margin of Safety Calculations - Temperature

Lens - Notched

$$MS_{lensnotched_t} := \frac{64 \cdot MPa}{2 \cdot 3.6 \cdot 25.3 \cdot MPa} - 1 \qquad MS_{lensnotched_t} = -0.649$$

Lens - Unnotched

$$MS_{lens_t} := \frac{64 \cdot MPa}{2 \cdot 1.0 \cdot 25.3 \cdot MPa} - 1 \qquad MS_{lens_t} = 0.265$$

Frame At Flexure

$$MS_{frameflexurelocalult_t} := \frac{289.58 \cdot MPa}{2 \cdot 350 \cdot MPa} - 1 \qquad MS_{frameflexurelocalult_t} = -0.586$$

$$MS_{frameflexurelocalyld_t} := \frac{241.317 \cdot MPa}{1.25 \cdot 350 \cdot MPa} - 1 \qquad MS_{frameflexurelocalyld_t} = -0.448$$

Frame Everywhere Else

$$MS_{frameflexureult_t} := \frac{289.58 \cdot MPa}{2 \cdot 130 \cdot MPa} - 1 \qquad MS_{frameflexureult_t} = 0.114$$

$$MS_{frameflexureyld_t} := \frac{241.317 \cdot MPa}{1.25 \cdot 130 \cdot MPa} - 1 \qquad MS_{frameflexureyld_t} = 0.485$$

Flexure at Attachments

$$MS_{flexurelocalult_t} := \frac{923.89 \cdot MPa}{2 \cdot 1340 \cdot MPa} - 1 \qquad MS_{flexurelocalult_t} = -0.655$$

$$MS_{flexurelocalyld_t} := \frac{868.73 \cdot MPa}{1.25 \cdot 1340 \cdot MPa} - 1 \qquad MS_{flexurelocalyld_t} = -0.481$$

Flexure Everywhere Else

$$MS_{flexureult_t} := \frac{923.89 \cdot MPa}{2 \cdot 400 \cdot MPa} - 1 \qquad MS_{flexureult_t} = 0.155$$

$$MS_{flexureyld_t} := \frac{868.73 \cdot MPa}{1.25 \cdot 400 \cdot MPa} - 1 \qquad MS_{flexureyld_t} = 0.737$$

Section 5 – Segmented Lens 1 in Frame 1

1. Finite Element Model

   A finite element model of a segmented lens 1 mounted in frame 1 was created. Plots of the model are shown below. The lens material is PMMA, the flexure material is Ti-6Al-4V, and the frame material is 6061-T6.

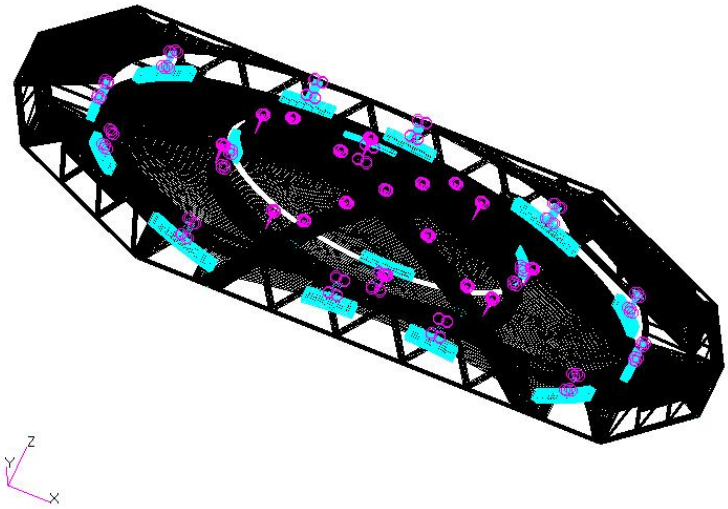


Figure 1: Lens 1 in Frame 1

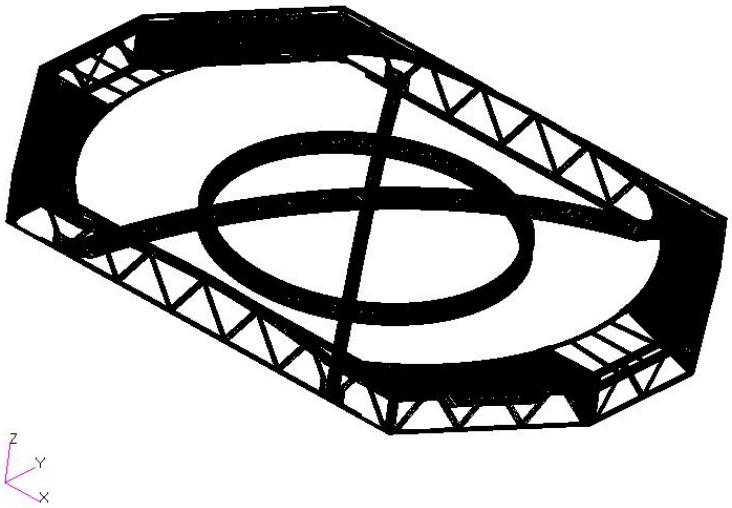


Figure 2: Frame 1

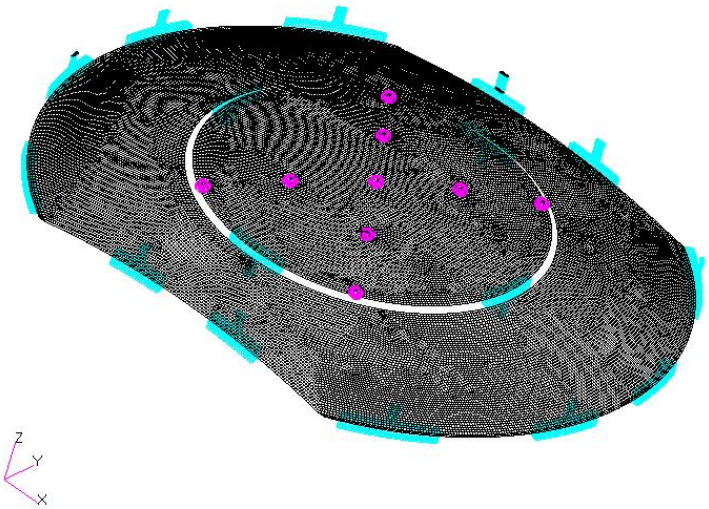


Figure 3: Lens 1 with Brackets and Flexures

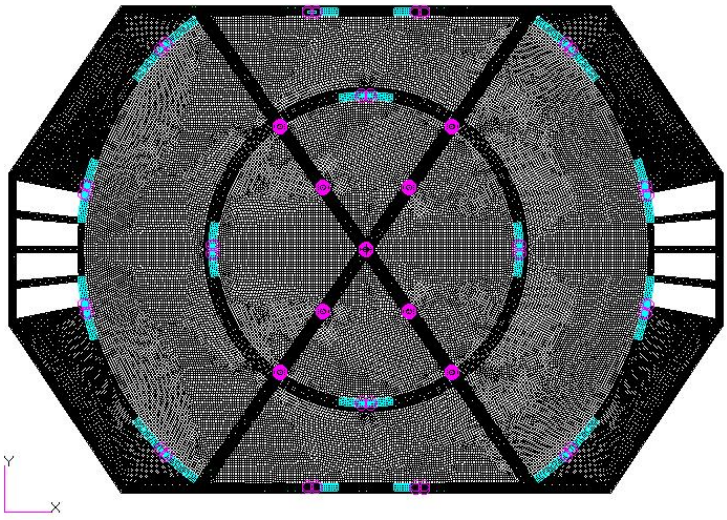


Figure 4: Lens 1 in Frame 1

2. Boundary Conditions

   The model was fixed in the three translation directions at the fasteners where the pallet attaches to the frame. The boundary conditions are shown in Figure 5 and Figure 6.

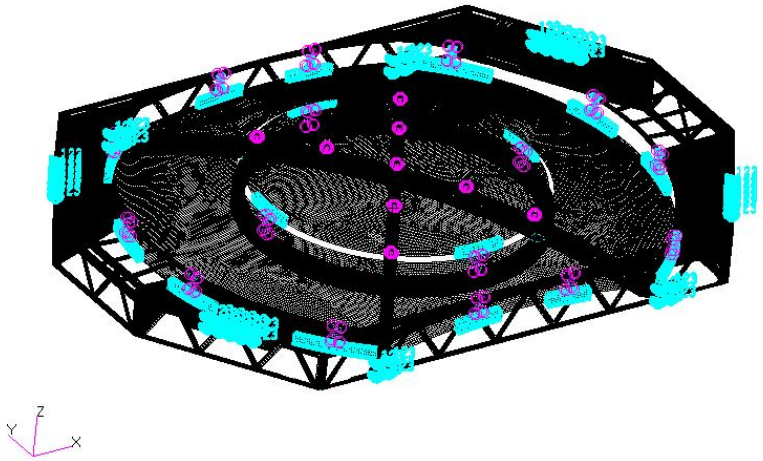


Figure 5: Frame Boundary Conditions

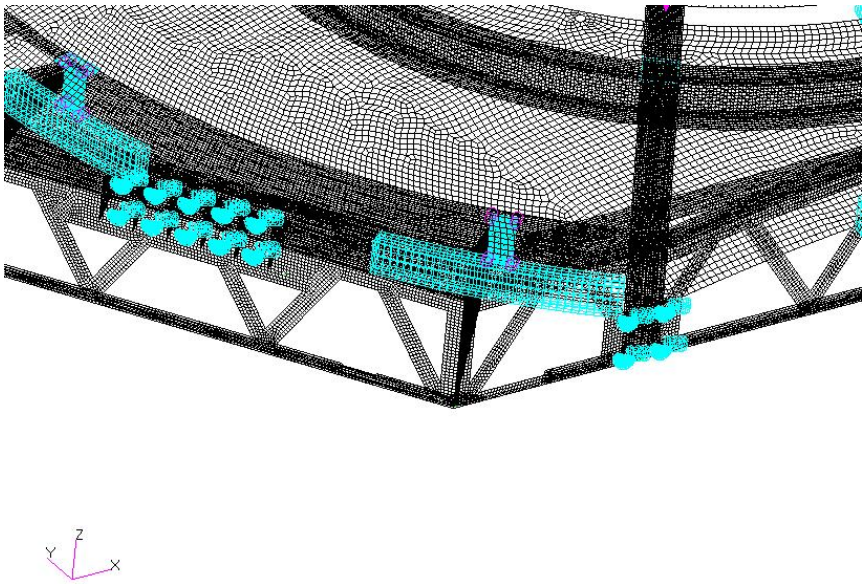
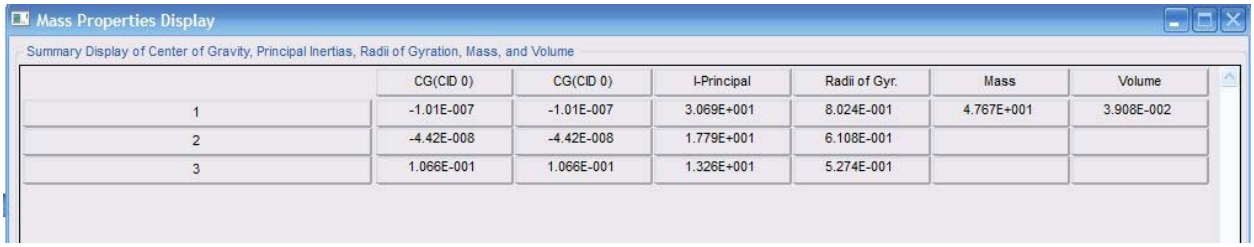


Figure 6: Close-up of Frame Boundary Conditions

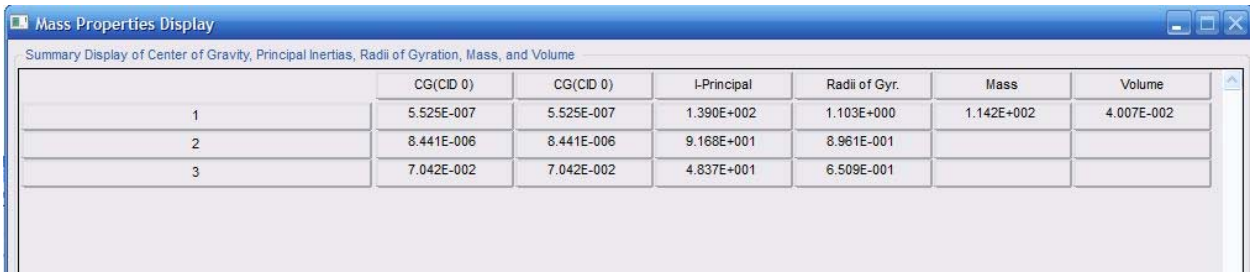
3. Mass

The mass of the lens in the model is 47.67 kg as shown below.



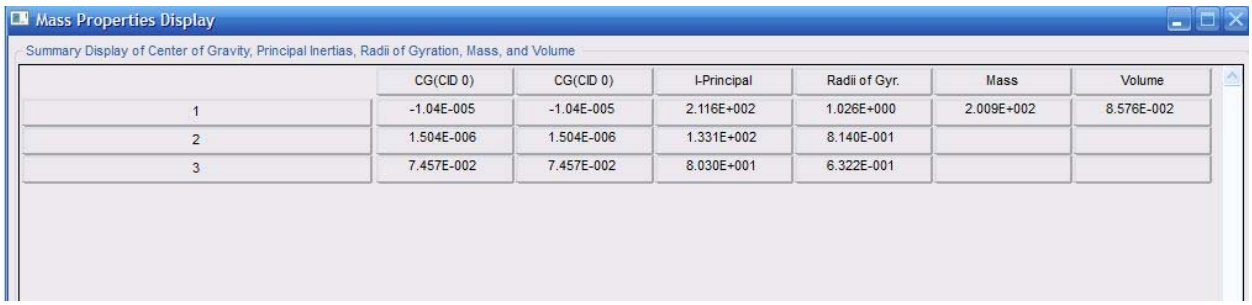
	CG(CID 0)	CG(CID 0)	I-Principal	Radii of Gyr.	Mass	Volume
1	-1.01E-007	-1.01E-007	3.069E+001	8.024E-001	4.767E+001	3.908E-002
2	-4.42E-008	-4.42E-008	1.779E+001	6.108E-001		
3	1.066E-001	1.066E-001	1.326E+001	5.274E-001		

The mass of the frame in the model is 114.2 kg.



	CG(CID 0)	CG(CID 0)	I-Principal	Radii of Gyr.	Mass	Volume
1	5.525E-007	5.525E-007	1.390E+002	1.103E+000	1.142E+002	4.007E-002
2	8.441E-006	8.441E-006	9.168E+001	8.961E-001		
3	7.042E-002	7.042E-002	4.837E+001	6.509E-001		

The total model mass is 200.9 kg.



	CG(CID 0)	CG(CID 0)	I-Principal	Radii of Gyr.	Mass	Volume
1	-1.04E-005	-1.04E-005	2.116E+002	1.026E+000	2.009E+002	8.576E-002
2	1.504E-006	1.504E-006	1.331E+002	8.140E-001		
3	7.457E-002	7.457E-002	8.030E+001	6.322E-001		

The mass in the CAD model is 200.1 kg.

4. Frequency

The frequency of the model is determined first. An integrated frequency of 50 Hz is required, or coupled loads will have to be worked with the launch vehicle. A design goal of 25 Hz was established for a frame assembly. The frequency of this assembly meets that goal with a frequency of 36.0 Hz. As the mass of the lens is not insignificant, this is showing that most likely the integrated frequency will be below 50 Hz. It will be a project decision as to whether to work coupled loads with the launch vehicle or add additional structure that would block lens viewing to increase the frequency.

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0 SUBCASE 1

R E A L E I G E N V A L U E S

MODE NO.	EXTRACTION ORDER	EIGENVALUE	RADIANS	CYCLES	GENERALIZED MASS	GENERALIZED STIFFNESS
1	1	5.130620E+04	2.265087E+02	3.604998E+01	1.000000E+00	5.130620E+04
2	2	7.115297E+04	2.667451E+02	4.245381E+01	1.000000E+00	7.115297E+04
3	3	7.779277E+04	2.789136E+02	4.439047E+01	1.000000E+00	7.779277E+04
4	4	7.999489E+04	2.828337E+02	4.501438E+01	1.000000E+00	7.999489E+04
5	5	9.466799E+04	3.076816E+02	4.896905E+01	1.000000E+00	9.466799E+04
6	6	1.027406E+05	3.205318E+02	5.101422E+01	1.000000E+00	1.027406E+05
7	7	1.030698E+05	3.210448E+02	5.109587E+01	1.000000E+00	1.030698E+05
8	8	1.039055E+05	3.223438E+02	5.130260E+01	1.000000E+00	1.039055E+05
9	9	1.050797E+05	3.241599E+02	5.159165E+01	1.000000E+00	1.050797E+05
10	10	1.099117E+05	3.315293E+02	5.276452E+01	1.000000E+00	1.099117E+05

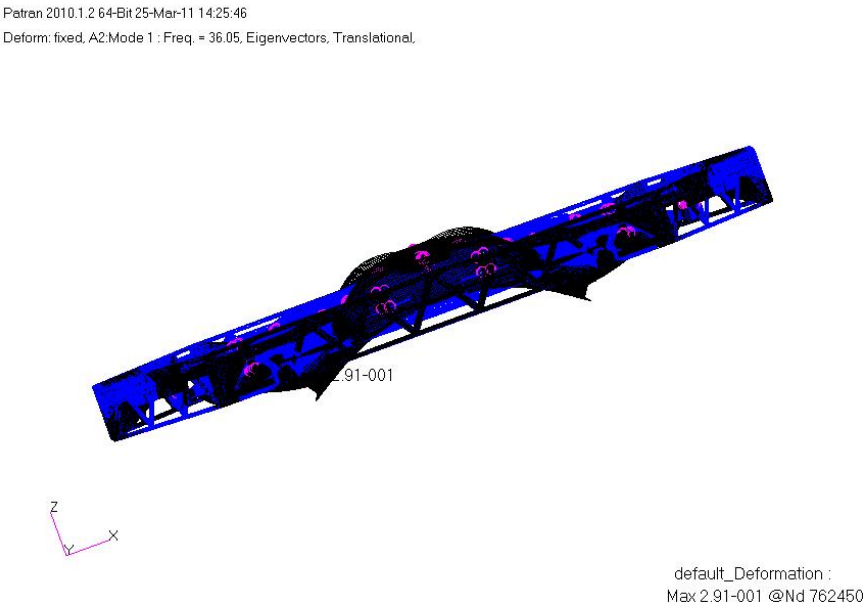

Figure 7: First Frequency Mode Shape

5. Launch Margins of Safety

The model was run using the calculated loads. The following load cases were used. Since the rotational accelerations need to be applied to the integrated model, the random accelerations were applied in all three axes simultaneously in this model to help account for the additional load in this partial model.

Load Case	Accel X (g's)	Accel Y (g's)	Accel Z (g's)
1	14.502	14.502	16.597
2	14.502	14.502	-16.597
3	14.502	-14.502	16.597
4	14.502	-14.502	-16.597

The maximum stress in the lens is shown in Figure 8 and the maximum deflection, in meters, in Figure 9. Using an untested factor of safety and the knockdown determined for the notch, the margin of safety is:

Stress, lens notched = 25.2 MPa, MS (ult) = -0.64

For the unnotched portion, the margin of safety is:

Stress, lens unnotched = 25.2 MPa, MS (ult) = +0.27

Another way to look at the stress plot is to plot the stress such that a positive margin is one color and a negative margin is a second color. This is shown in Figure 10 where the areas identified in red have a negative margin and those in blue have a positive margin using the notch knockdown. The peak stresses are occurring in the areas where the brackets are holding the lens, which may or may not be notched. Currently in the model, the lens is attached to the bracket as if the lens and bracket are one continuous solid. The next iteration of the model should update the attachments to be more realistic to determine if the peaking at the attachments is truly as high as predicted. These peaks also need to be compared with the notch locations to determine if any peaks coincide with a notch.

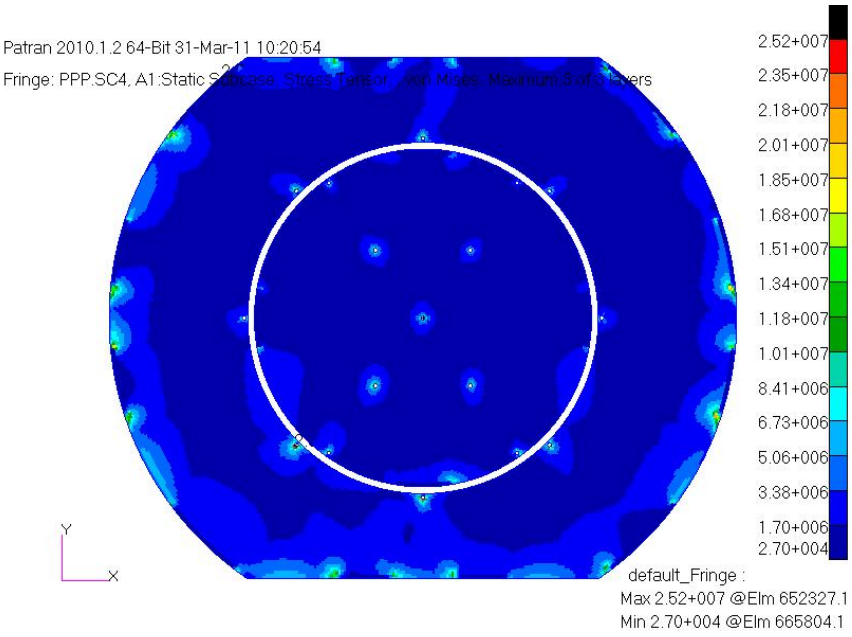

Figure 8: Maximum Stress in Lens 1

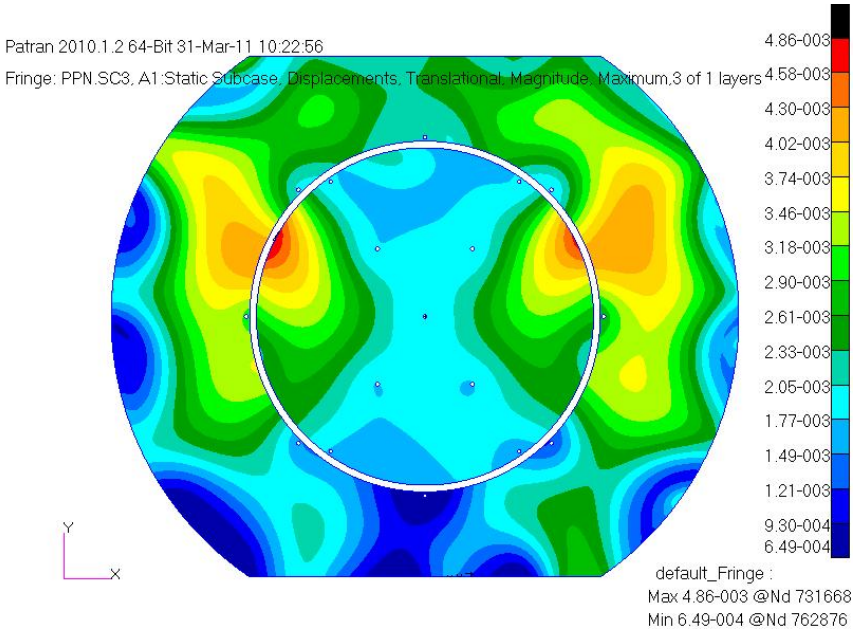

Figure 9: Maximum Deflection in Lens 1

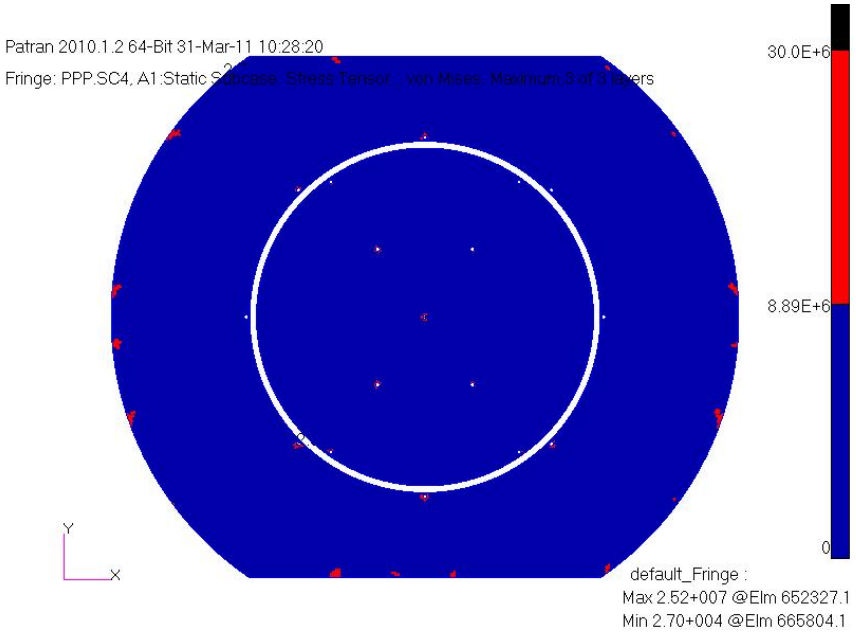

Figure 10 Negative Margin Plot of Lens 1

The maximum stress in the frame is shown in Figure 11 with the maximum deflection, in meters, in Figure 12. Using untested factors of safety and ignoring local peaking at attachments, the margins of safety are:

Stress, frame = 125 MPa, MS (ult) = +0.15
MS (yld) = +0.54

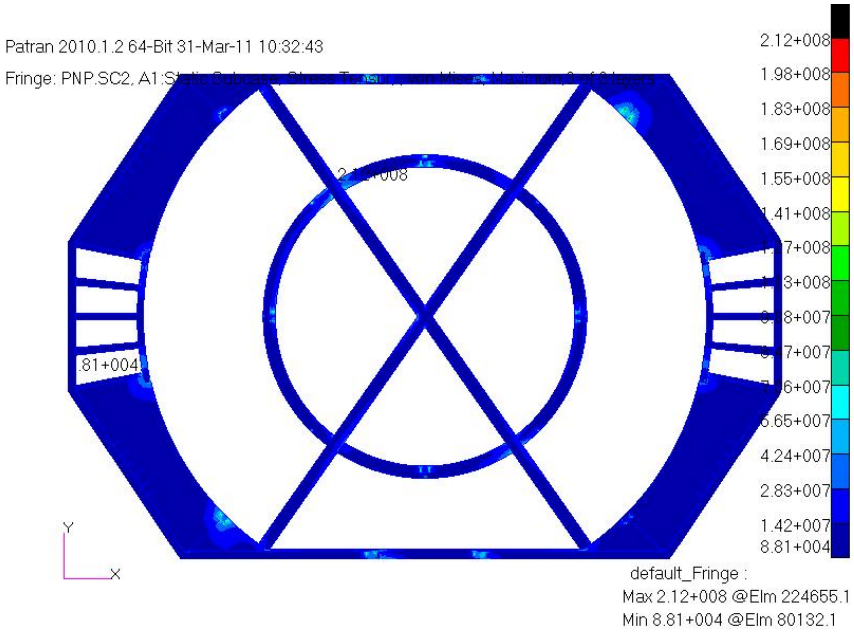

Figure 11: Maximum Stress in Frame 1

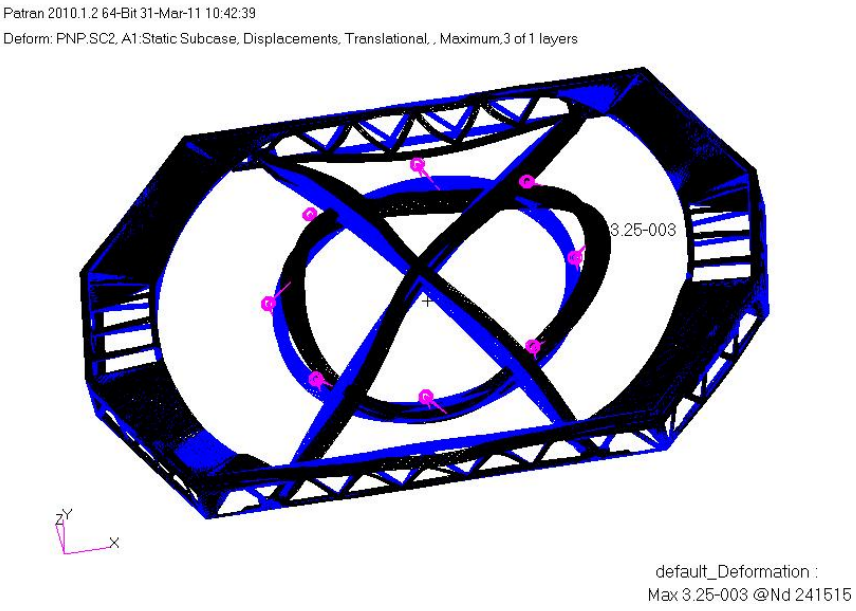

Figure 12: Maximum Deflection in Frame 1

The maximum stress in the flexure is shown in Figure 13. Using untested factors of safety and ignoring local peaking at attachments, the margins of safety are:

Stress, flexure at attachments = 1150 MPa, MS (ult) = -0.60
MS (yld) = -0.40

Stress, flexure everywhere else = 450 MPa, MS (ult) = +0.02
MS (yld) = +0.54

It's worth noting that the only places where the negative margin exists are at the flexure attachment to the frame and lens bracket. Everywhere else the margins of safety are positive. As the intent of this model was to assess the flexure in general and not necessarily the flexure attachment to the frame, the flanges of the flexure were not modeled. The next iteration of the model should include the flanges to more accurately model the flexure and determine if a margin issue exists or not. On the positive side, the flexure body is showing positive margins and will carry the required load.

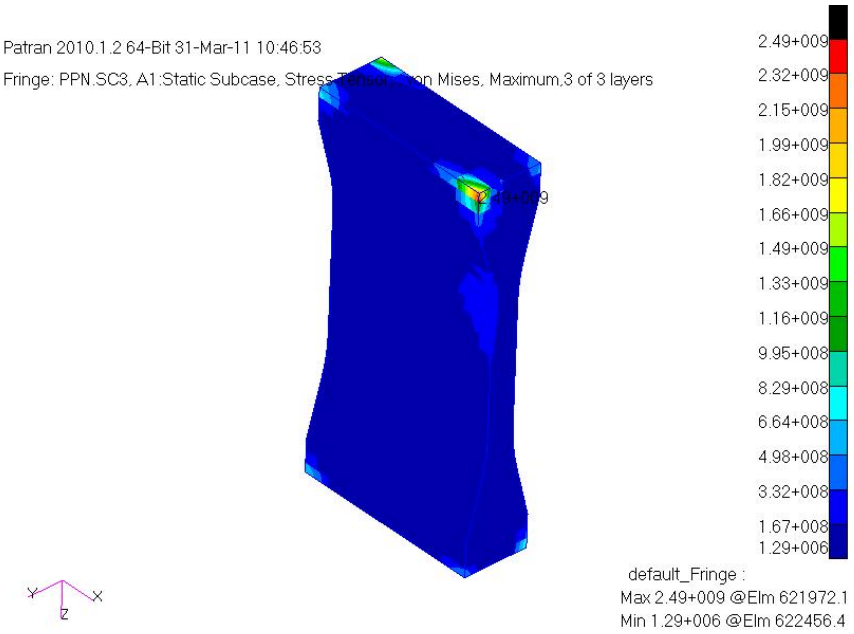

Figure 13: Maximum Stress in Flexure

6. Thermal Margins of Safety

The temperature of the model was varied between -20 C and + 40 C, with the assembly temperature of room temperature. The peak stress in the lens, flexure, and frame are shown in Figures 14, Figure 15, and Figure 16. Figure 17 and Figure 18 show the maximum displacement, in meters, of the assembly and lens only due to the change in temperature.

Using untested factors of safety, the margins of safety are:

Stress, lens notched = 29.1 MPa, MS (ult) = -0.70

Stress, lens unnotched = 29.1 MPa, MS (ult) = +0.10

Stress, frame at constraints = 388 MPa, MS (ult) = -0.63
MS (yld) = -0.51

Stress, frame everywhere else = 140 MPa, MS (ult) = +0.03
MS (yld) = +0.37

Stress, flexure at attachments = 1270 MPa, MS (ult) = -0.64
MS (yld) = -0.46

Stress, flexure everywhere else = 450 MPa, MS (ult) = +0.02
MS (yld) = +0.54

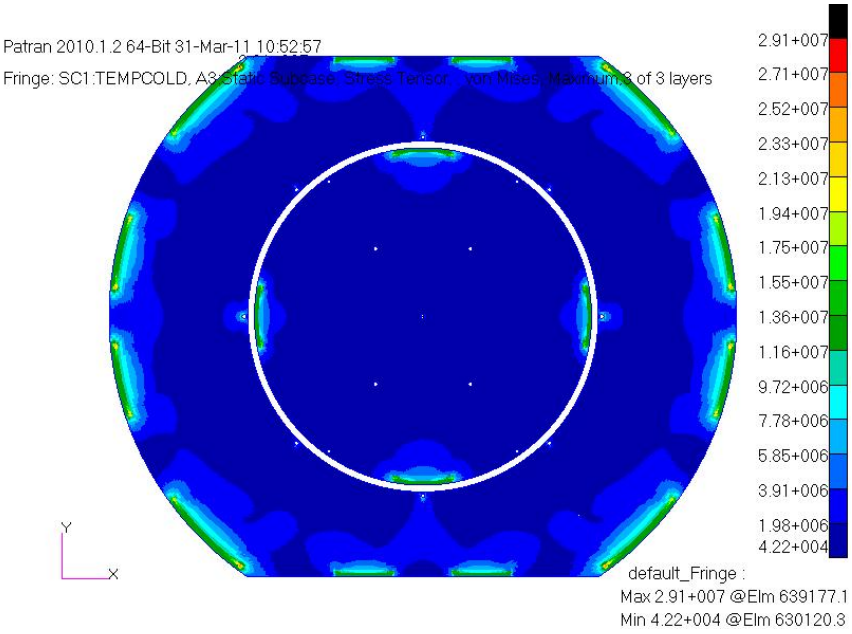

Figure 14: Maximum Stress in Lens 1 due to Thermal

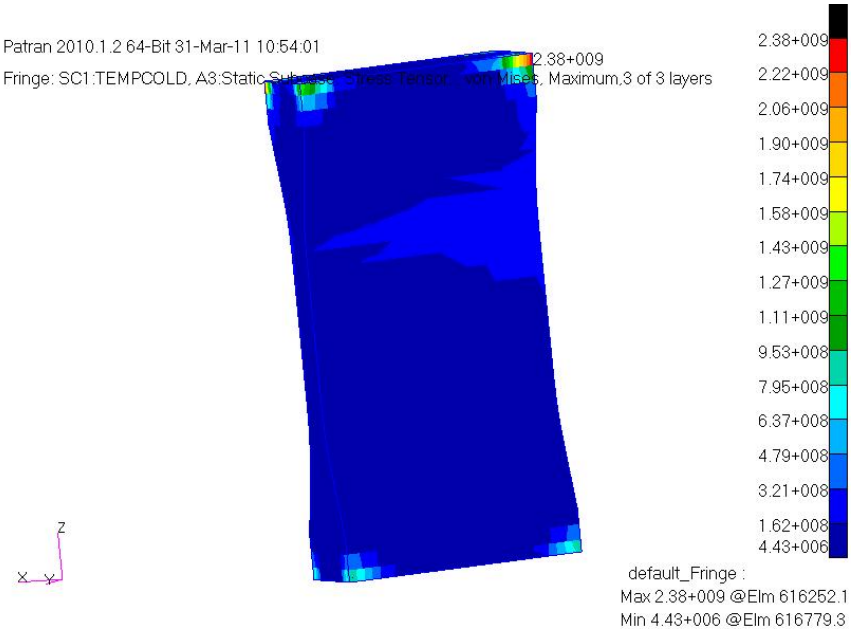

Figure 15: Maximum Stress in Flexure due to Thermal

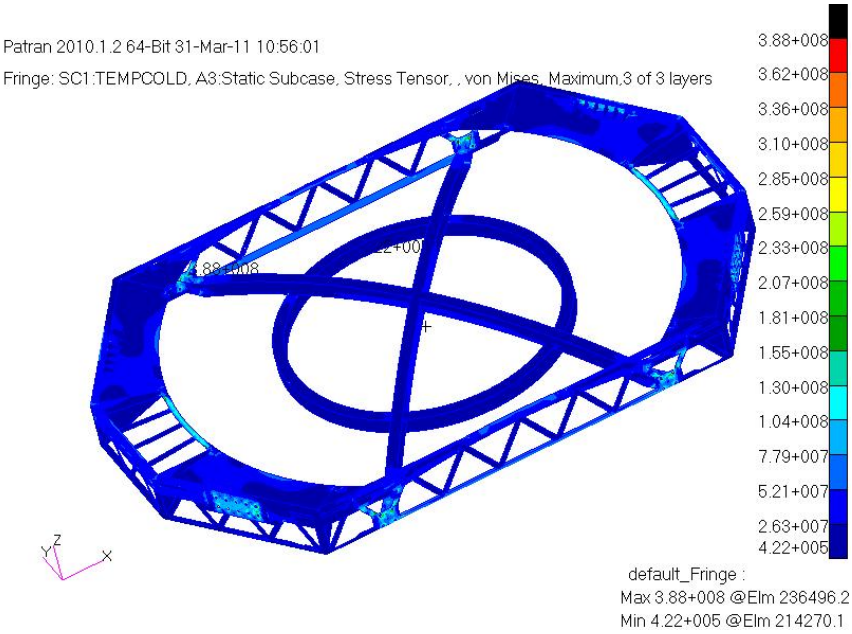

Figure 16: Maximum Stress in Frame 3 due to Thermal

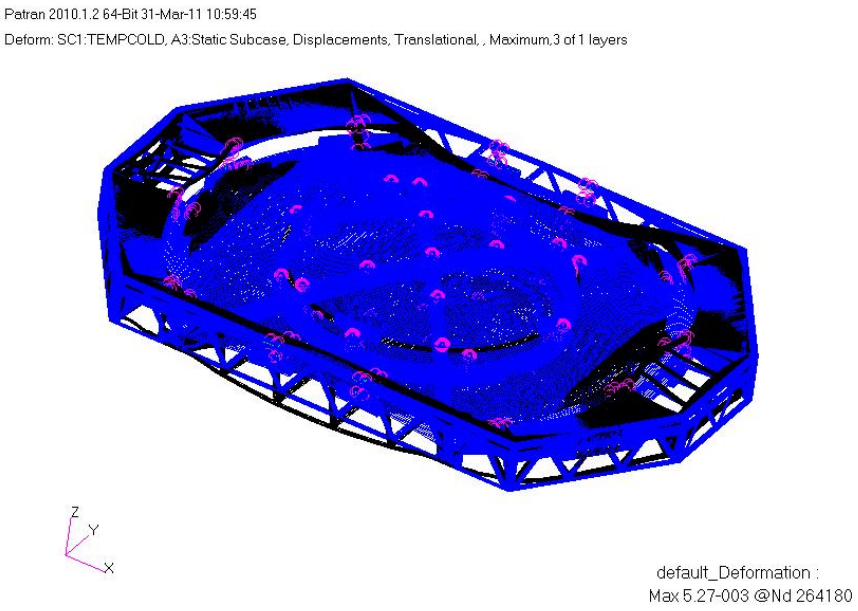

Figure 17: Maximum Deflection due to Thermal

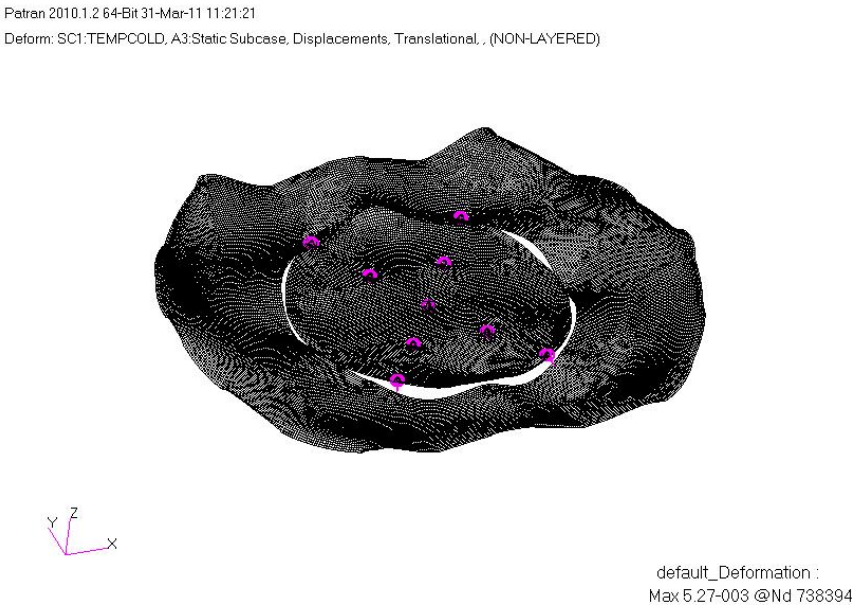

Figure 18: Maximum Deflection of Lens due to Thermal

The analysis shows the same problem areas as in the launch acceleration load cases. The same design changes and lens notch location information will also improve these margins. Also, the fixed

constraint does not take into account that the pallet is expanding or contracting with a temperature change. The effect of the pallet on the frame needs to be considered in future iterations and will reduce the peak stresses in the frame shown in this analysis.

7. Model Checks

Time did not permit a complete quality check of the model. The following checks were performed on the model.

A free-free run was performed to verify the first six frequencies are zero and the seventh frequency is significantly higher. The results are shown below.

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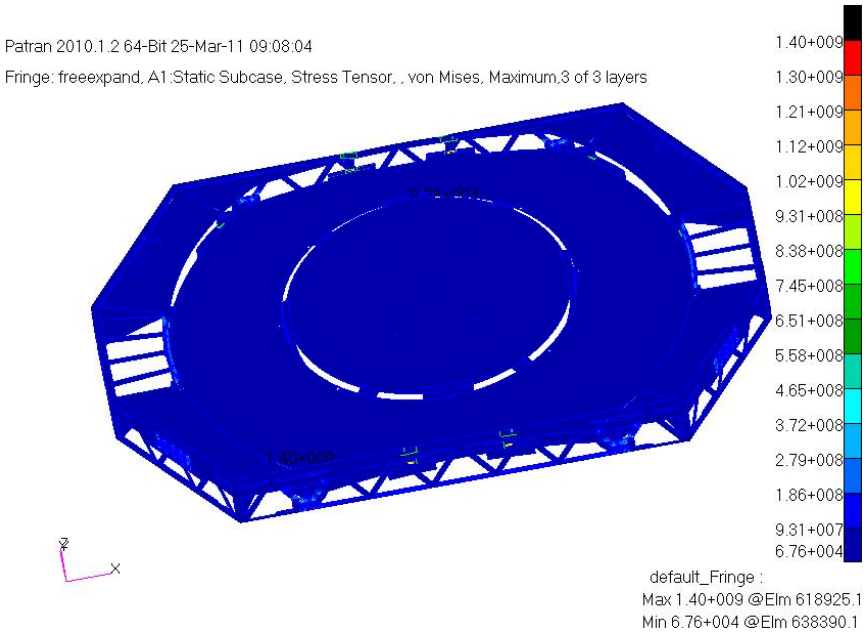
0 SUBCASE 1

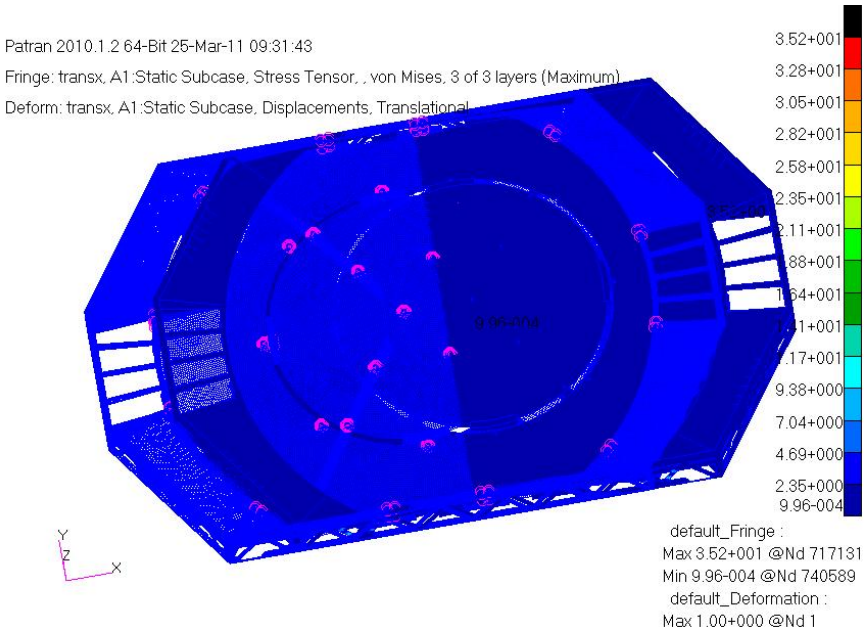
R E A L E I G E N V A L U E S

MODE NO.	EXTRACTION ORDER	EIGENVALUE	RADIANS	CYCLES	GENERALIZED MASS	GENERALIZED STIFFNESS
1	1	-4.254290E-06	2.062593E-03	3.282719E-04	1.000000E+00	-4.254290E-06
2	2	-2.930630E-06	1.711908E-03	2.724587E-04	1.000000E+00	-2.930630E-06
3	3	-2.045194E-06	1.430103E-03	2.276079E-04	1.000000E+00	-2.045194E-06
4	4	-8.437364E-07	9.185512E-04	1.461920E-04	1.000000E+00	-8.437364E-07
5	5	4.405713E-07	6.637554E-04	1.056399E-04	1.000000E+00	4.405713E-07
6	6	1.392793E-06	1.180167E-03	1.878293E-04	1.000000E+00	1.392793E-06
7	7	1.261654E+04	1.123234E+02	1.787682E+01	1.000000E+00	1.261654E+04
8	8	2.201314E+04	1.483682E+02	2.361354E+01	1.000000E+00	2.201314E+04
9	9	3.598800E+04	1.897050E+02	3.019249E+01	1.000000E+00	3.598800E+04
10	10	4.010014E+04	2.002502E+02	3.187081E+01	1.000000E+00	4.010014E+04

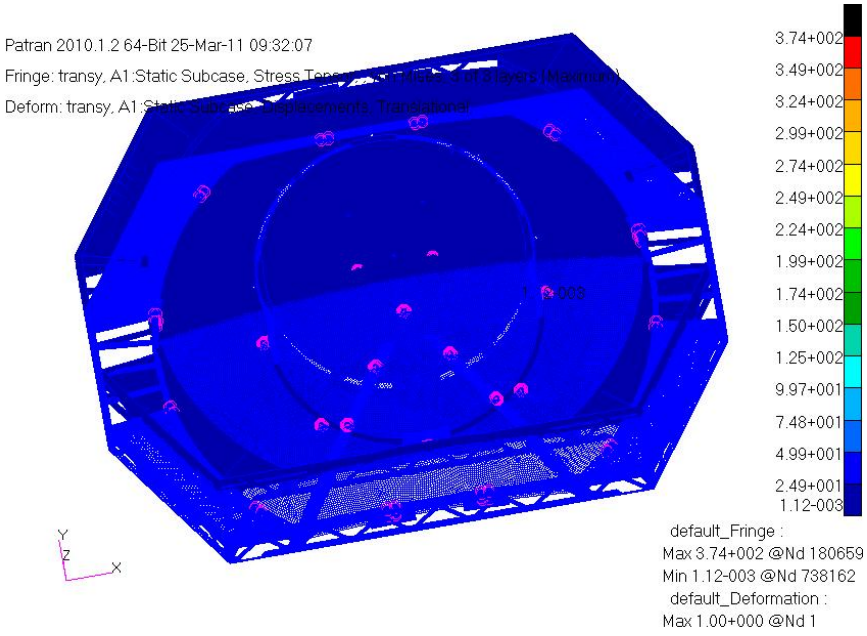
A free expansion check was performed to verify the stress is close to zero. There are expected peak stresses occurring at the flexure interfaces at the RBEs. Otherwise the stress is very low.



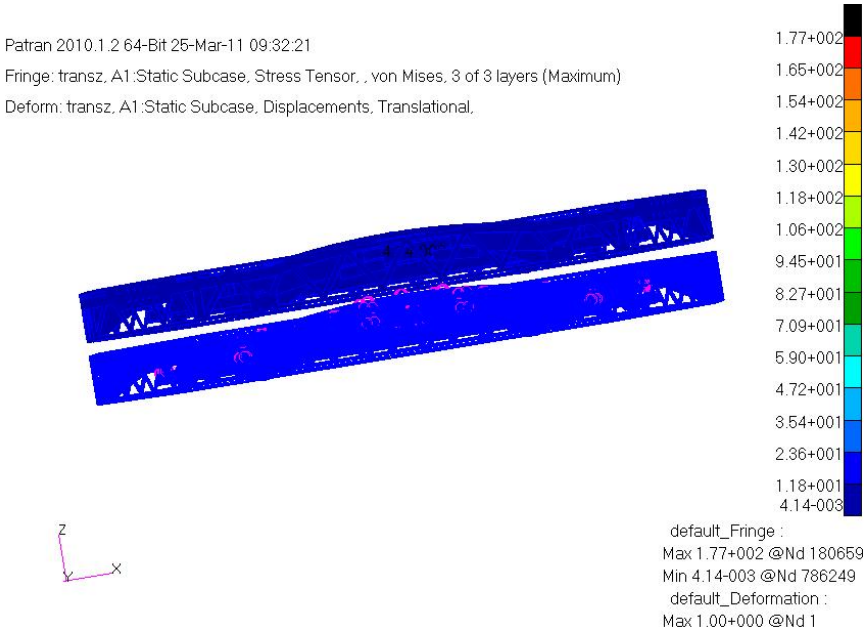
An enforced displacement check was performed to verify the stress is close to zero. The max stress from the six load cases is around 1510 Pa or 1 psi.



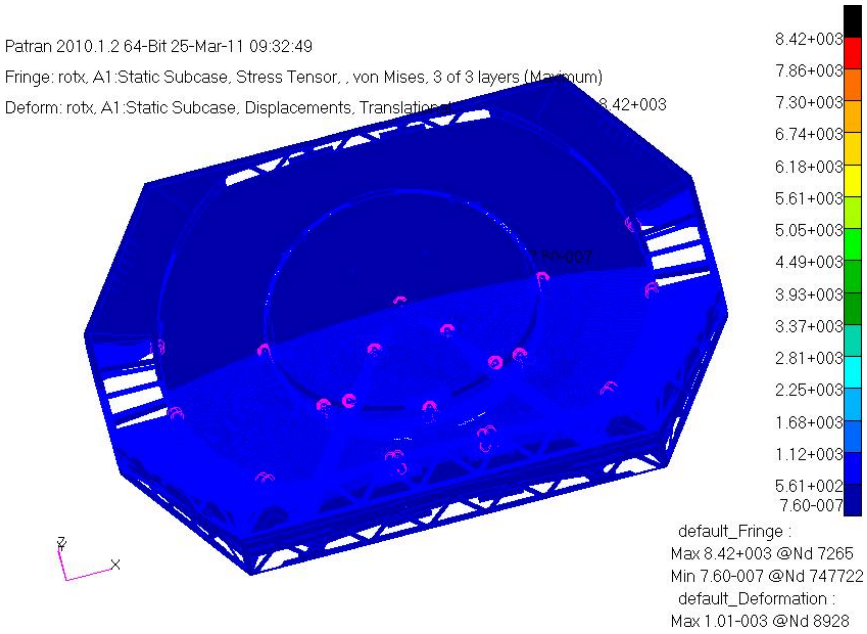
Enforced Displacement in X Translation



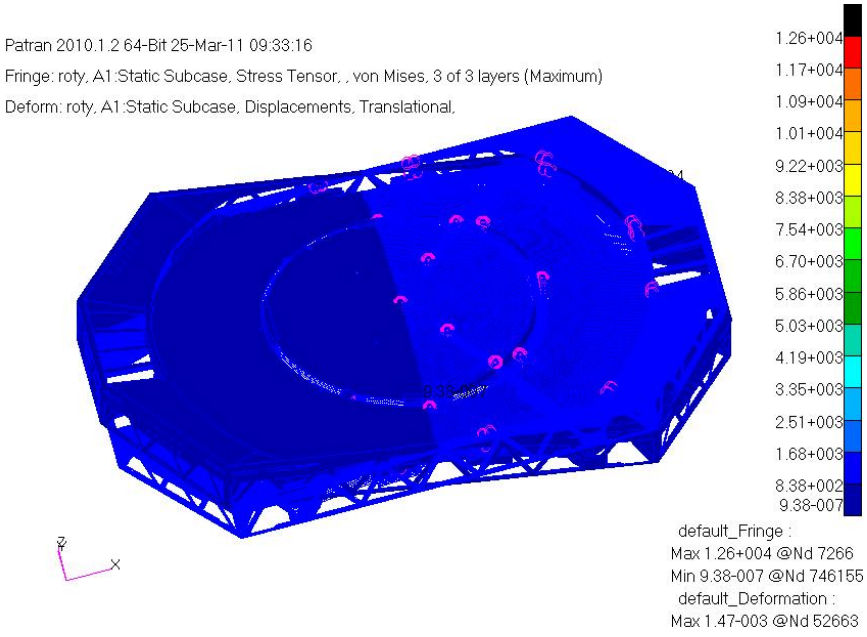
Enforced Displacement in Y Translation



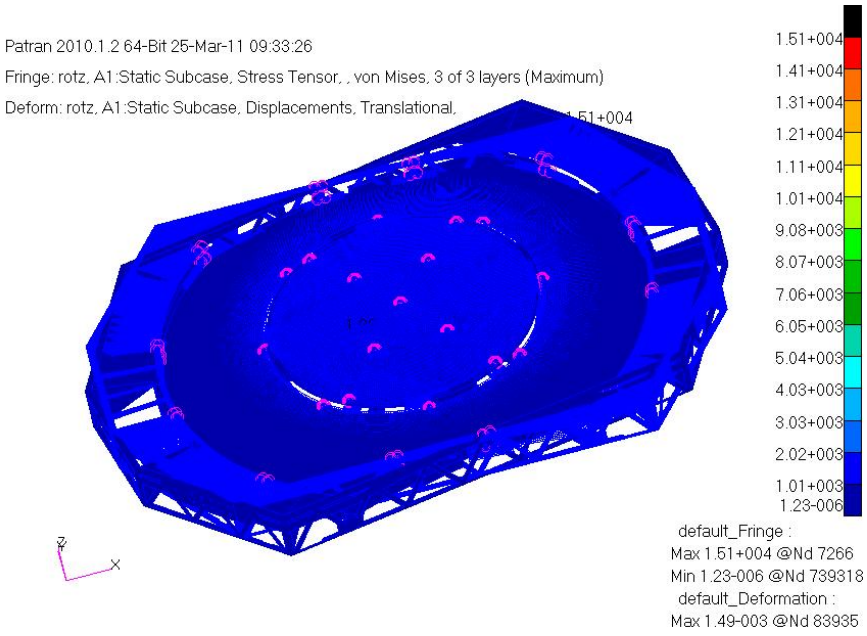
Enforced Displacement in Z Translation



Enforced Displacement in X Rotation

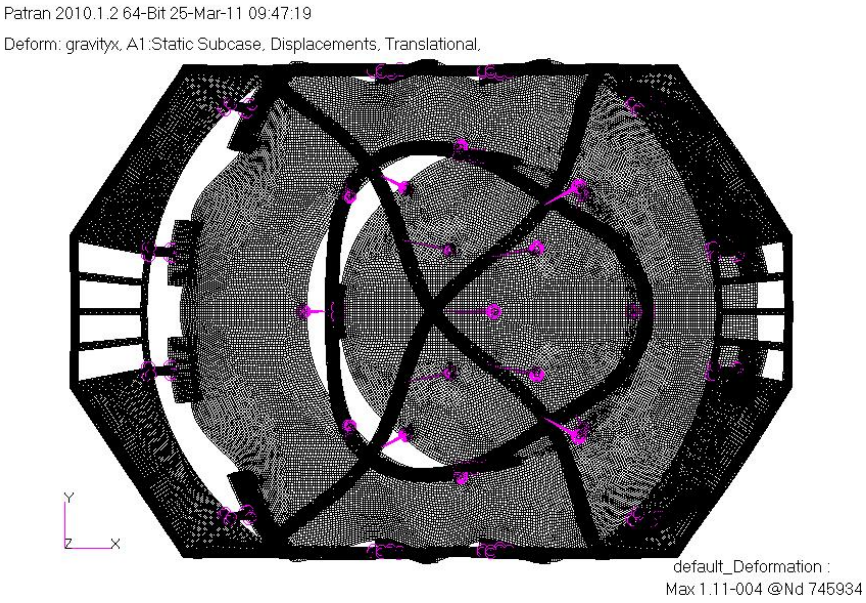


Enforced Displacement in Y Rotation

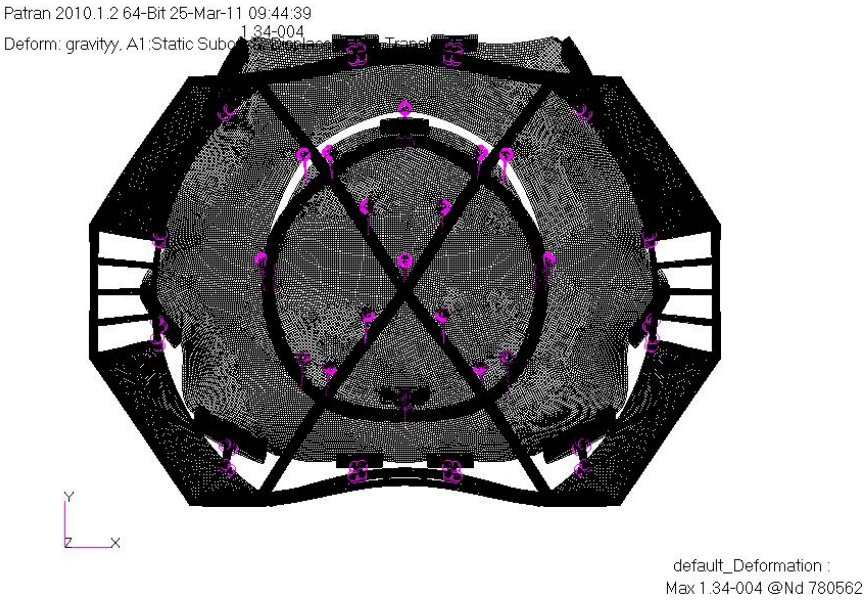


Enforced Displacement in Z Rotation

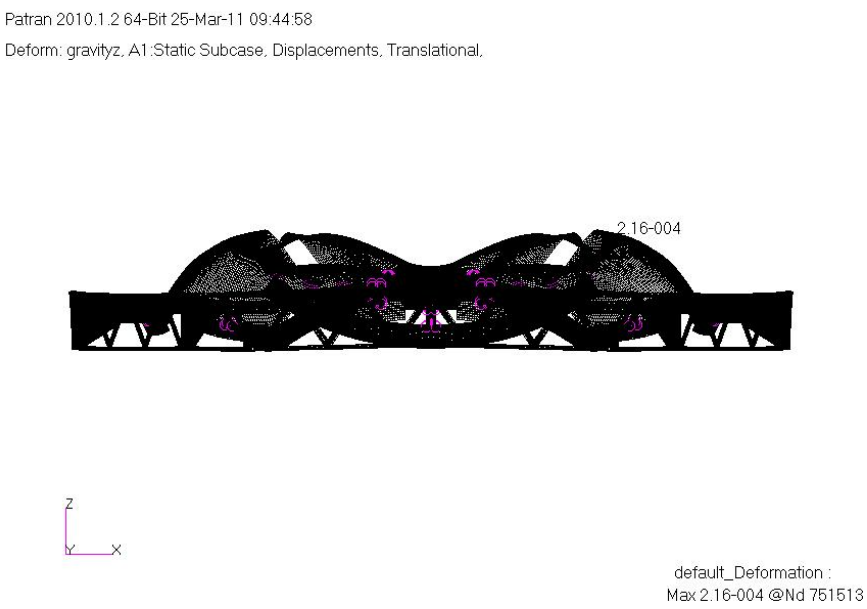
The model was run with one g applied in each axis at a time to verify the model behaved properly. The displacement plots from the three load cases are shown below.



One G in X Direction



One G in Y Direction



One G in Z Direction

The residual vector error for the stress runs is verified to be less than 10e-6. The following are the errors from the Nastran runs.

Epsilon from Strength Analysis

```
1    MSC.NASTRAN JOB CREATED ON 23-SEP-10 AT 11:55:43                    MARCH  25, 2011  NX NASTRAN  6/25/10   PAGE  1584

0                                                                                                          SUBCASE 1
 *** SYSTEM INFORMATION MESSAGE 6916 (DFMSYN)
     DECOMP ORDERING METHOD CHOSEN: BEND, ORDERING METHOD USED: BEND
 *** USER INFORMATION MESSAGE 5293 (SSG3A)
    FOR DATA BLOCK KLL
    LOAD SEQ. NO.            EPSILON             EXTERNAL WORK      EPSILONS LARGER THAN 0.001 ARE FLAGGED WITH ASTERISKS
               1        -8.2999872E-13          2.5410490E+01
               2        -7.1296567E-12          2.5417074E+01
               3        -4.6081220E-12          2.5409473E+01
               4        -1.1141504E-12          2.5414650E+01
```

Epsilon from Thermal Cold Analysis

```
1    MSC.NASTRAN JOB CREATED ON 23-SEP-10 AT 11:55:43                    MARCH  31, 2011  NX NASTRAN  6/25/10   PAGE  1583

0                                                                                                          SUBCASE 1
 *** SYSTEM INFORMATION MESSAGE 6916 (DFMSYN)
     DECOMP ORDERING METHOD CHOSEN: BEND, ORDERING METHOD USED: BEND
 *** USER INFORMATION MESSAGE 5293 (SSG3A)
    FOR DATA BLOCK KLL
    LOAD SEQ. NO.            EPSILON             EXTERNAL WORK      EPSILONS LARGER THAN 0.001 ARE FLAGGED WITH ASTERISKS
               1        -3.6305523E-14          5.2216177E+03
```

Epsilon from Thermal Hot Analysis

```
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0                                                                                                          SUBCASE 1
 *** SYSTEM INFORMATION MESSAGE 6916 (DFMSYN)
     DECOMP ORDERING METHOD CHOSEN: BEND, ORDERING METHOD USED: BEND
 *** USER INFORMATION MESSAGE 5293 (SSG3A)
    FOR DATA BLOCK KLL
    LOAD SEQ. NO.            EPSILON             EXTERNAL WORK      EPSILONS LARGER THAN 0.001 ARE FLAGGED WITH ASTERISKS
               1        -2.8709213E-14          1.1213586E+03
```

Epsilon from One G Analysis

```
1    MSC.NASTRAN JOB CREATED ON 23-SEP-10 AT 11:55:43                    MARCH  25, 2011  NX NASTRAN  6/25/10   PAGE  1584

0                                                                                                        SUBCASE 1
 *** SYSTEM INFORMATION MESSAGE 6916 (DFMSYN)
     DECOMP ORDERING METHOD CHOSEN: BEND, ORDERING METHOD USED: BEND
 *** USER INFORMATION MESSAGE 5293 (SSG3A)
    FOR DATA BLOCK KLL
    LOAD SEQ. NO.            EPSILON             EXTERNAL WORK      EPSILONS LARGER THAN 0.001 ARE FLAGGED WITH ASTERISKS
               1         6.1273388E-13          3.5150174E-02
               2         7.7664139E-13          3.2565337E-02
               3        -5.6613585E-12          4.0556855E-02
```

Epsilon from Enforced Displacement Analysis

```
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0                                                                                                        SUBCASE 1
 *** SYSTEM INFORMATION MESSAGE 6916 (DFMSYN)
     DECOMP ORDERING METHOD CHOSEN: BEND, ORDERING METHOD USED: BEND
 *** USER INFORMATION MESSAGE 5293 (SSG3A)
    FOR DATA BLOCK KLL
    LOAD SEQ. NO.            EPSILON             EXTERNAL WORK      EPSILONS LARGER THAN 0.001 ARE FLAGGED WITH ASTERISKS
               1        -1.0612282E-13          1.0431238E+09
1    MSC.NASTRAN JOB CREATED ON 23-SEP-10 AT 11:55:43                    MARCH  25, 2011  NX NASTRAN  6/25/10   PAGE  9420

0                                                                                                        SUBCASE 2
 *** SYSTEM INFORMATION MESSAGE 6916 (DFMSYN)
     DECOMP ORDERING METHOD CHOSEN: BEND, ORDERING METHOD USED: BEND
 *** USER INFORMATION MESSAGE 5293 (SSG3A)
    FOR DATA BLOCK KLL
    LOAD SEQ. NO.            EPSILON             EXTERNAL WORK      EPSILONS LARGER THAN 0.001 ARE FLAGGED WITH ASTERISKS
               2        -8.5432641E-15          1.1881157E+09
1    MSC.NASTRAN JOB CREATED ON 23-SEP-10 AT 11:55:43                    MARCH  25, 2011  NX NASTRAN  6/25/10   PAGE  9421

0                                                                                                        SUBCASE 3
 *** SYSTEM INFORMATION MESSAGE 6916 (DFMSYN)
     DECOMP ORDERING METHOD CHOSEN: BEND, ORDERING METHOD USED: BEND
 *** USER INFORMATION MESSAGE 5293 (SSG3A)
    FOR DATA BLOCK KLL
    LOAD SEQ. NO.            EPSILON             EXTERNAL WORK      EPSILONS LARGER THAN 0.001 ARE FLAGGED WITH ASTERISKS
               3        -1.1160332E-13          8.7484666E+08
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0                                                                                                        SUBCASE 4
 *** SYSTEM INFORMATION MESSAGE 6916 (DFMSYN)
     DECOMP ORDERING METHOD CHOSEN: BEND, ORDERING METHOD USED: BEND
 *** USER INFORMATION MESSAGE 5293 (SSG3A)
    FOR DATA BLOCK KLL
    LOAD SEQ. NO.            EPSILON             EXTERNAL WORK      EPSILONS LARGER THAN 0.001 ARE FLAGGED WITH ASTERISKS
               4         2.3426944E-10          2.5631197E-02
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0                                                                                                        SUBCASE 5
 *** SYSTEM INFORMATION MESSAGE 6916 (DFMSYN)
     DECOMP ORDERING METHOD CHOSEN: BEND, ORDERING METHOD USED: BEND
 *** USER INFORMATION MESSAGE 5293 (SSG3A)
    FOR DATA BLOCK KLL
    LOAD SEQ. NO.            EPSILON             EXTERNAL WORK      EPSILONS LARGER THAN 0.001 ARE FLAGGED WITH ASTERISKS
               5        -4.1759969E-09          2.6794109E-02
1    MSC.NASTRAN JOB CREATED ON 23-SEP-10 AT 11:55:43                    MARCH  25, 2011  NX NASTRAN  6/25/10   PAGE  9424

0                                                                                                        SUBCASE 6
 *** SYSTEM INFORMATION MESSAGE 6916 (DFMSYN)
     DECOMP ORDERING METHOD CHOSEN: BEND, ORDERING METHOD USED: BEND
 *** USER INFORMATION MESSAGE 5293 (SSG3A)
    FOR DATA BLOCK KLL
    LOAD SEQ. NO.            EPSILON             EXTERNAL WORK      EPSILONS LARGER THAN 0.001 ARE FLAGGED WITH ASTERISKS
               6        -2.5108170E-08          6.0559814E-03
```

Epsilon from Free Thermal Expansion Analysis

```
0                                                                                                        SUBCASE 1
 *** USER INFORMATION MESSAGE 5293 (SSG3A)
    FOR DATA BLOCK KLL
    LOAD SEQ. NO.            EPSILON             EXTERNAL WORK      EPSILONS LARGER THAN 0.001 ARE FLAGGED WITH ASTERISKS
               1        -6.1066956E-14          1.3463525E+04
```

Margin of Safety Calculations - Accelerations

Lens - Notched

$$MS_{lensnotched_a} := \frac{64 \cdot MPa}{2 \cdot 3.6 \cdot 25.2 \cdot MPa} - 1 \qquad MS_{lensnotched_a} = -0.647$$

Lens - Unnotched

$$MS_{lens_a} := \frac{64 \cdot MPa}{2 \cdot 1.0 \cdot 25.2 \cdot MPa} - 1 \qquad MS_{lens_a} = 0.27$$

Frame

$$MS_{frameflexureult_a} := \frac{289.58 \, MPa}{2 \cdot 125 \cdot MPa} - 1 \qquad MS_{frameflexureult_a} = 0.158$$

$$MS_{frameflexureyld_a} := \frac{241.317 \, MPa}{1.25 \cdot 125 \cdot MPa} - 1 \qquad MS_{frameflexureyld_a} = 0.544$$

Flexure at Attachments

$$MS_{flexurelocalult_a} := \frac{923.89 \, MPa}{2 \cdot 1150 \cdot MPa} - 1 \qquad MS_{flexurelocalult_a} = -0.598$$

$$MS_{flexurelocalyld_a} := \frac{868.73 \, MPa}{1.25 \cdot 1150 \cdot MPa} - 1 \qquad MS_{flexurelocalyld_a} = -0.396$$

Flexure Everywhere Else

$$MS_{flexureult_a} := \frac{923.89 \, MPa}{2 \cdot 450 \cdot MPa} - 1 \qquad MS_{flexureult_a} = 0.027$$

$$MS_{flexureyld_a} := \frac{868.73 \, MPa}{1.25 \cdot 450 \cdot MPa} - 1 \qquad MS_{flexureyld_a} = 0.544$$

Margin of Safety Calculations - Temperature

Lens - Notched

$$MS_{lensnotched_t} := \frac{64 \cdot MPa}{2 \cdot 3.6 \cdot 29.1 \cdot MPa} - 1 \qquad MS_{lensnotched_t} = -0.695$$

Lens - Unnotched

$$MS_{lens_t} := \frac{64 \cdot MPa}{2 \cdot 1.0 \cdot 29.1 \cdot MPa} - 1 \qquad MS_{lens_t} = 0.1$$

Frame At Constraints

$$MS_{frameflexurelocalult_t} := \frac{289.58 \cdot MPa}{2 \cdot 388 \cdot MPa} - 1 \qquad MS_{frameflexurelocalult_t} = -0.627$$

$$MS_{frameflexurelocalyld_t} := \frac{241.317 \cdot MPa}{1.25 \cdot 388 \cdot MPa} - 1 \qquad MS_{frameflexurelocalyld_t} = -0.502$$

Frame Everywhere Else

$$MS_{frameflexureult_t} := \frac{289.58 \cdot MPa}{2 \cdot 140 \cdot MPa} - 1 \qquad MS_{frameflexureult_t} = 0.034$$

$$MS_{frameflexureyld_t} := \frac{241.317 \cdot MPa}{1.25 \cdot 140 \cdot MPa} - 1 \qquad MS_{frameflexureyld_t} = 0.379$$

Flexure at Attachments

$$MS_{flexurelocalult_t} := \frac{923.89 \cdot MPa}{2 \cdot 1270 \cdot MPa} - 1 \qquad MS_{flexurelocalult_t} = -0.636$$

$$MS_{flexurelocalyld_t} := \frac{868.73 \cdot MPa}{1.25 \cdot 1270 \cdot MPa} - 1 \qquad MS_{flexurelocalyld_t} = -0.453$$

Flexure Everywhere Else

$$MS_{flexureult_t} := \frac{923.89 \cdot MPa}{2 \cdot 450 \cdot MPa} - 1 \qquad MS_{flexureult_t} = 0.027$$

$$MS_{flexureyld_t} := \frac{868.73 \cdot MPa}{1.25 \cdot 450 \cdot MPa} - 1 \qquad MS_{flexureyld_t} = 0.544$$

JEM-EUSO Baseline Optical Design
Lens and Frame Stress And Dynamics Analysis

Lisa Roth
Alex Sobey
Roy Young

NASA MSFC

- Project Mgt.
- Systems Eng.
- Optical frames
- Ground flashers

UAHuntsville

- Optics testing
- Public data release
- Simulations

Vanderbilt University

- Theory
- Simulations
- Analysis

Space Sciences Laboratory, University of California Berkeley

- Simulations
- Education & Public Outreach

UCLA

- Event Reconstruction
- Neutrino theory

Design Considerations

The lens frame/support design was conducted with consideration to several design requirements including:

Overall system mass

1st Lens Support/Frame = <150 kg (including 15% margin)
2nd Lens Support/Frame = <100 kg (including 15% margin)
3rd Lens Support/Frame = <100 kg (including 15% margin)

Lens manufacturing constraints (depth limitation in Z-axis): < 210 mm

Stress/deformation caused by change in temperature of interfacing material:

Operating Temperature: -10 to 30°C
Non-Operation Temperature: -45°C to +55°C
Lens Lateral Displacement (positional accuracy) < ± 2.5 mm
Lens Axial Displacement (coaxial tolerance) < ± 2.5 mm
Lens Tilt (parallel tolerance) < ± 2.5 mm

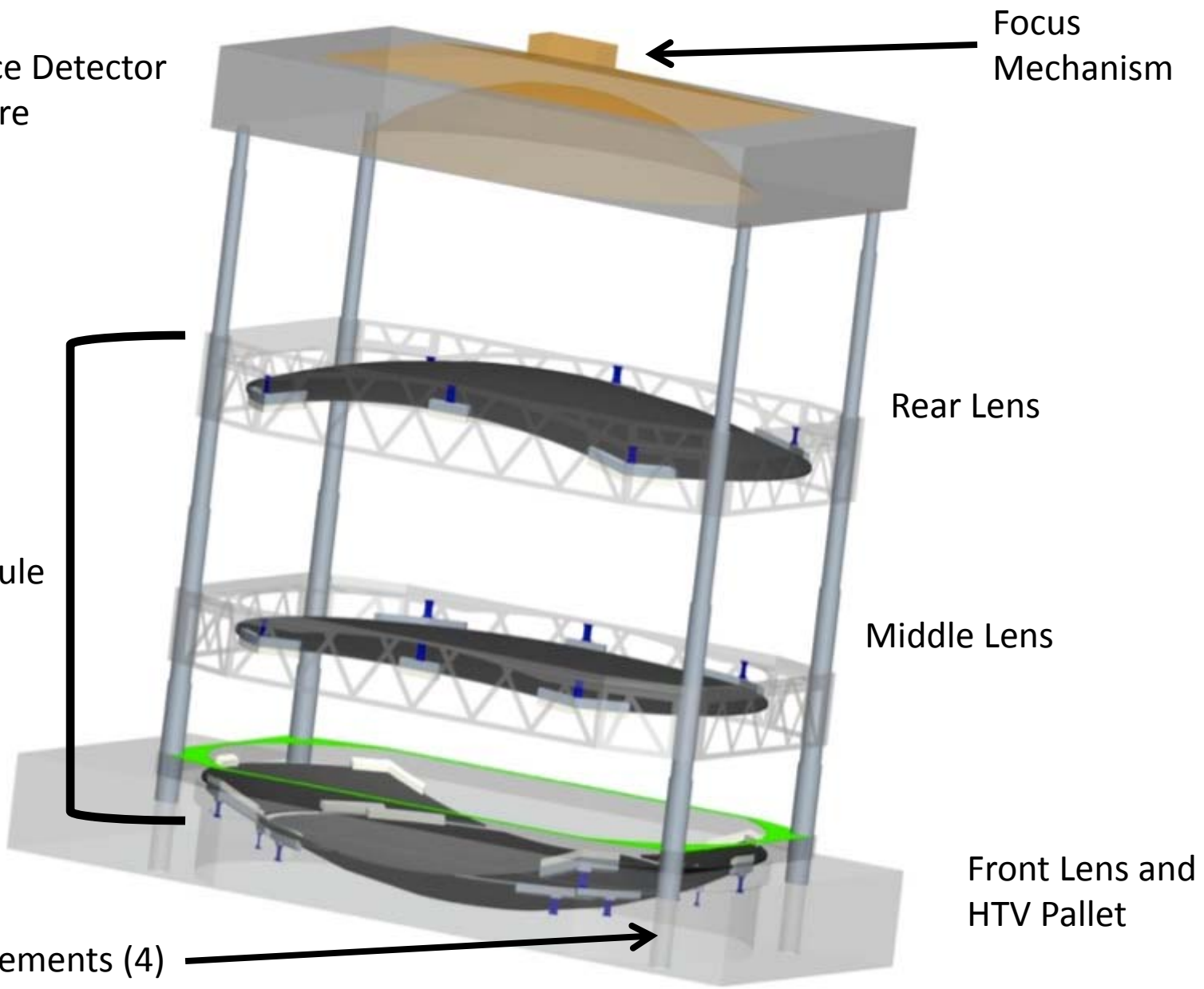
Stress caused by launch loads: 16.6g quasi-static (each axis independently)

Structural Natural Frequency:

Launch ≥ 25 Hz
Operational > 2 Hz

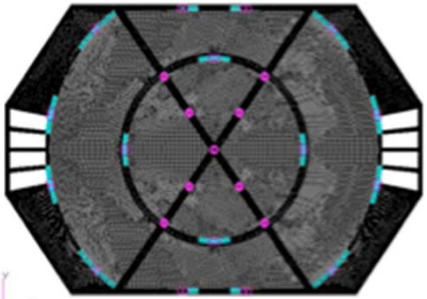
Obscuration of support structure: < 4%

JEM-EUSO Instrument

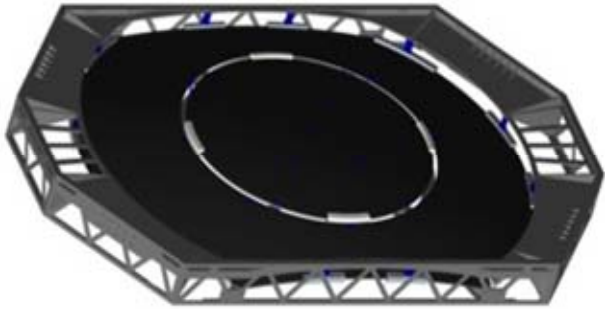


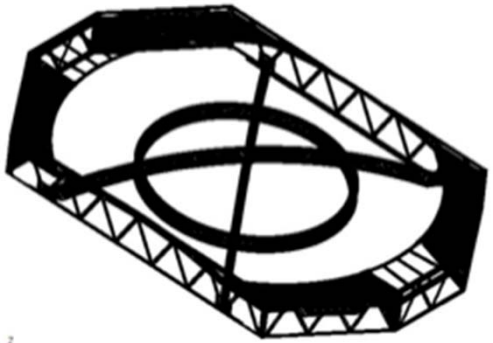
Preliminary Lens Frame Designs

Frame 1

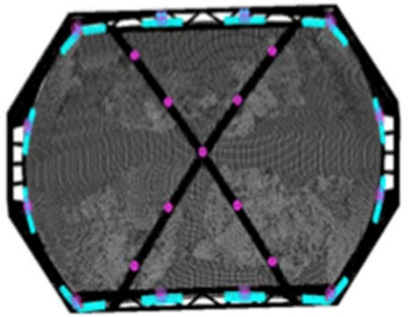


Lens 1 with Brackets (blue) and Flexures (pink) in Frame

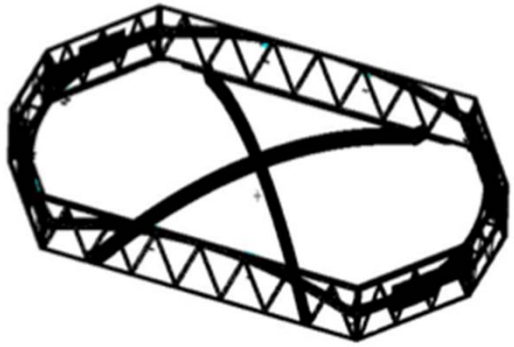




Frame 3



Lens 3 with Brackets (blue) and Flexures (pink) in Frame



Ti flexures
Al 6061 frames, support

Preliminary Lens Frame Designs

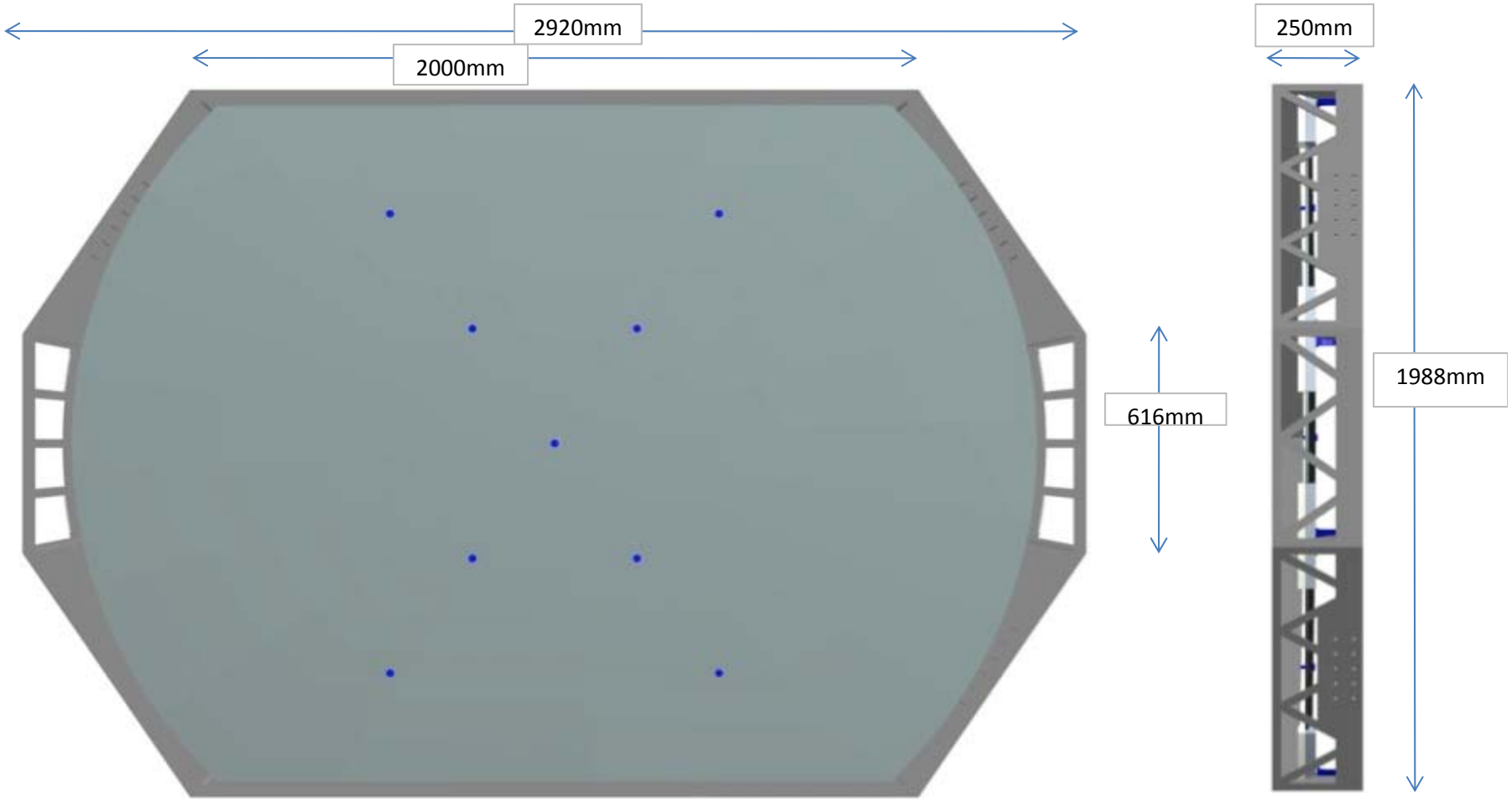


Table *Mass budget (Baseline optics and preliminary structure design).*

Parts	BEE [kg]	Margin [%]	Total [kg]	Comments
1st lens (Front)	46.94	15	53.98	PMMA-000 10 mm thickness
Frame of the 1st lens	123.15-	15	141.62	
Stop (iris)	-	-	-	Included in 2nd lens frame
2nd lens (Middle)	56.17	15	64.59	PMMA-000 10 mm thickness
Frame of the 2nd lens	84.64	15	97.34	
3rd lens (Rear)	57.20	15	65.78	PMMA-000 10 mm thickness
Frame of the 3rd lens	83.46	15	95.98	
Focusing adjust system	20	15	23	
Total	***471.56***		***542.30***	

Notes: Frame 1 mass can be reduced once details of the Modified EP are provided
Overall mass optimization of the OM will occur in PhaseA

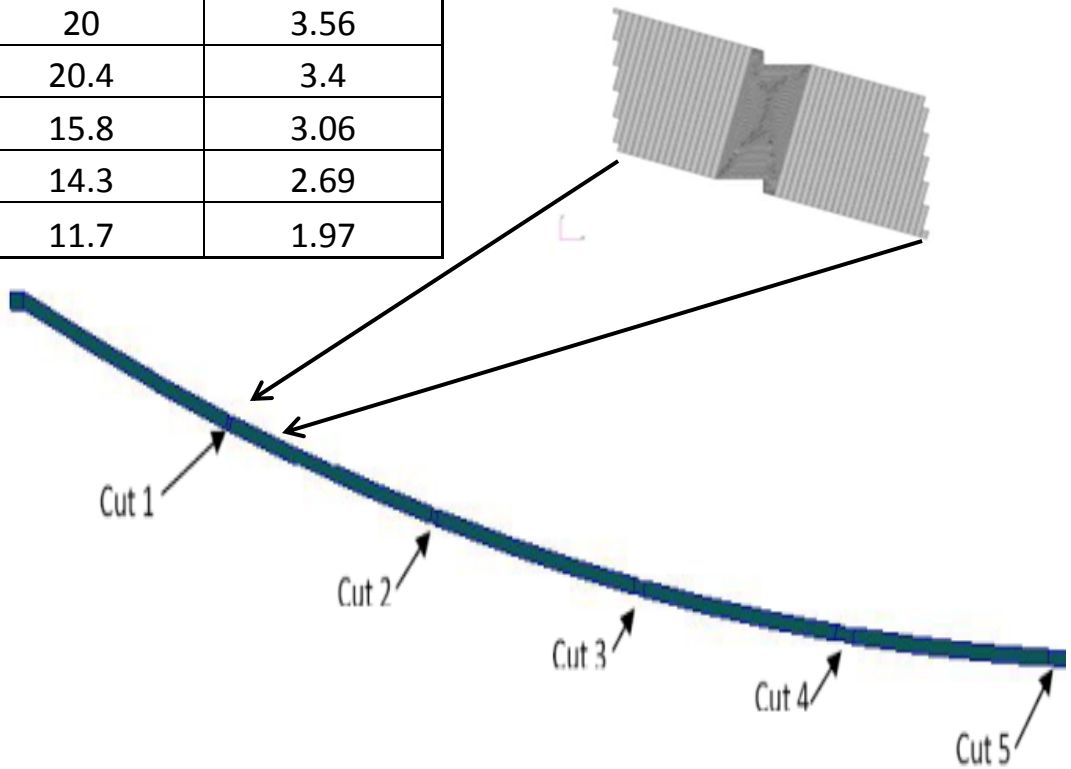
Study Parameters

- Used loads from NASDA-ESPC-2857 Rev C
  - Quasi: ±3.0 g's in X and Y, ±6.0 g's in Z, ±30.0 rad/s^2 rotation in all three axis
  - Random: ±14.188 g's assuming damping of 10, and frequency of 80 Hz to maximize load.
- Considered translation accelerations
- Random loads applied in all three directions simultaneously
- Safety factors are 2.0 for Ultimate and 1.25 for Yield
- Thermal: assembly temperature of 21°C, maximum and minimum temperatures are +40°C and -20°C.

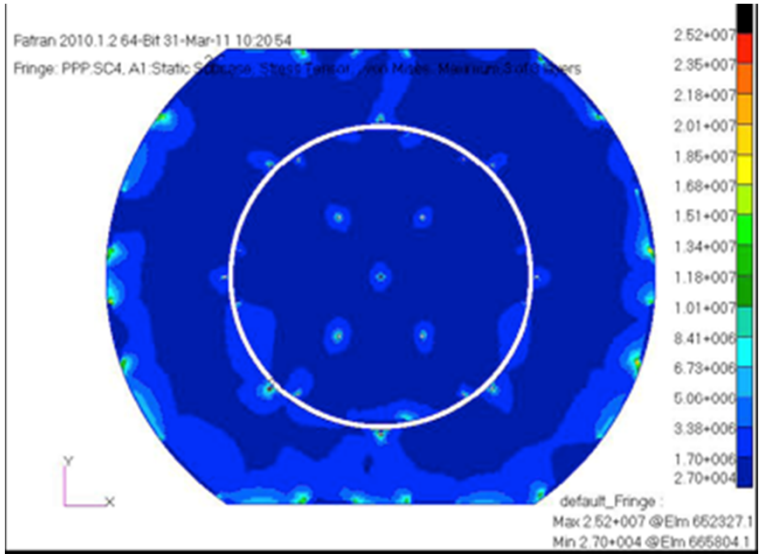
Fresnel Facet Modeling

Analysis showed the stress is increased by a factor of 3.56 due to the Fresnel facets. This factor was introduced in all stress calculations

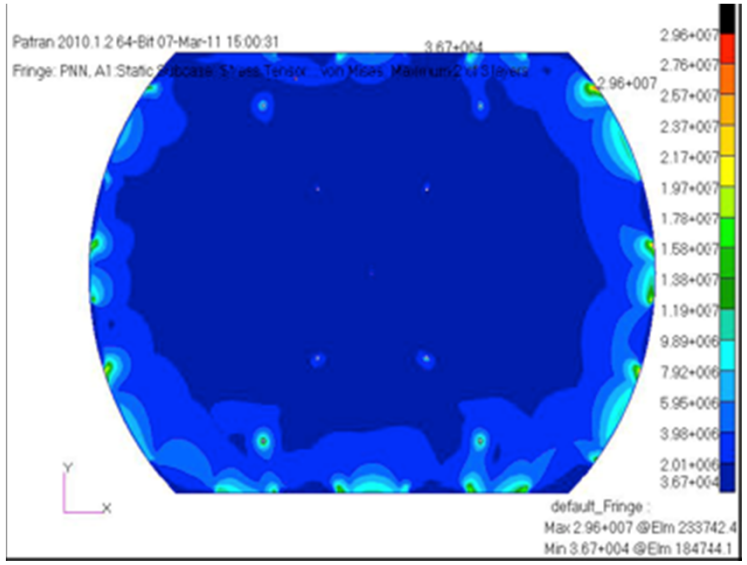
Summary of Peak Stresses for each cut location					
	Stress with no cut	Stress at cut (thick=40mm)	Stress at cut (10mm)	Stress at cut (5mm)	Stress Concentration Factor
Cut 1	5.62	19.3	20	20	3.56
Cut 2	6	18.2	20.4	20.4	3.4
Cut 3	5.17	15.1	15.8	15.8	3.06
Cut 4	5.32	13.7	14.3	14.3	2.69
Cut 5	5.95	10.6	11.7	11.7	1.97

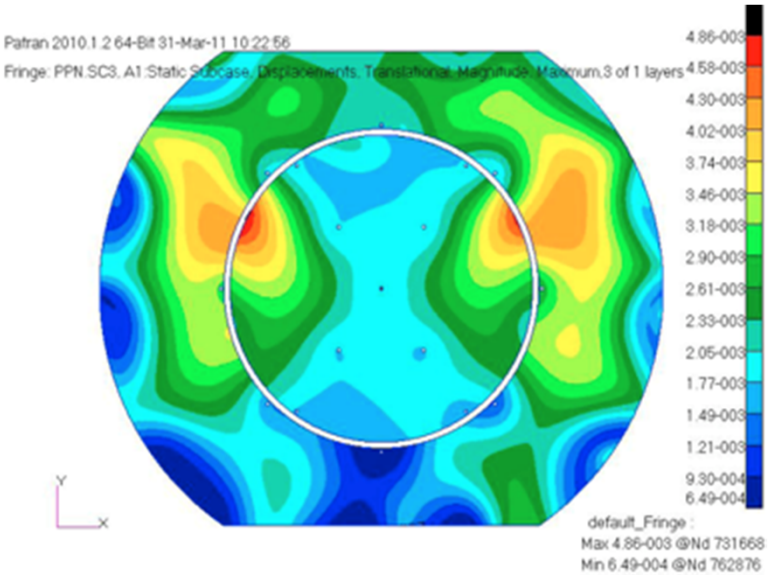


Structural Analysis Results

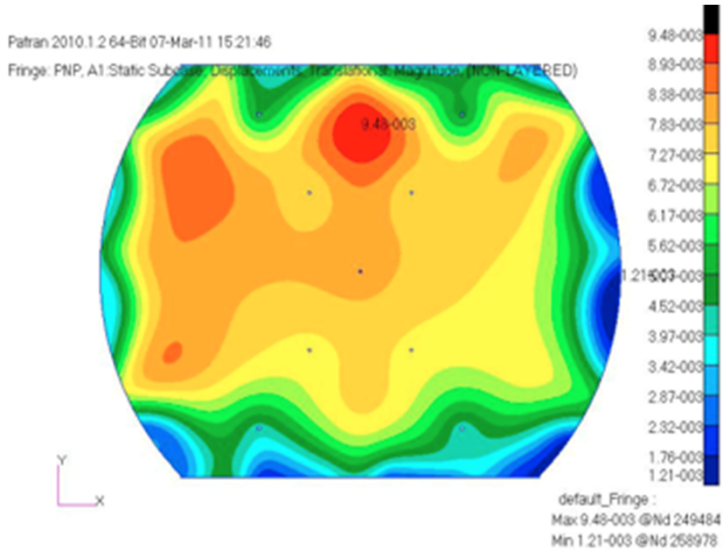


Maximum Stress (Pascals)



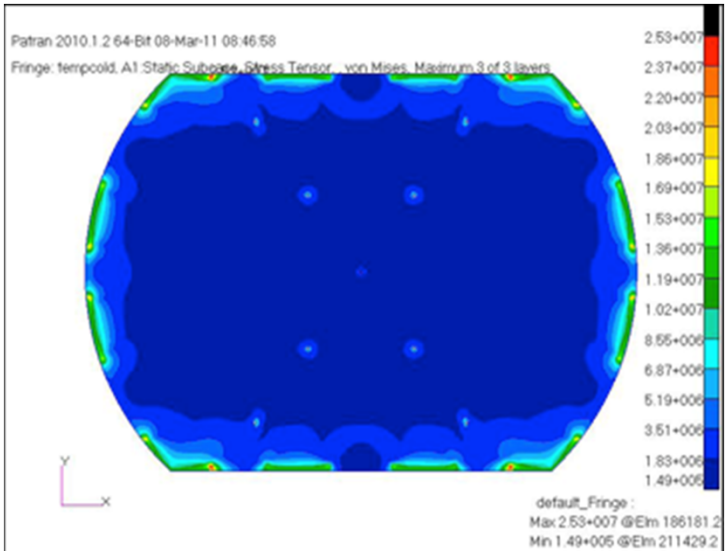


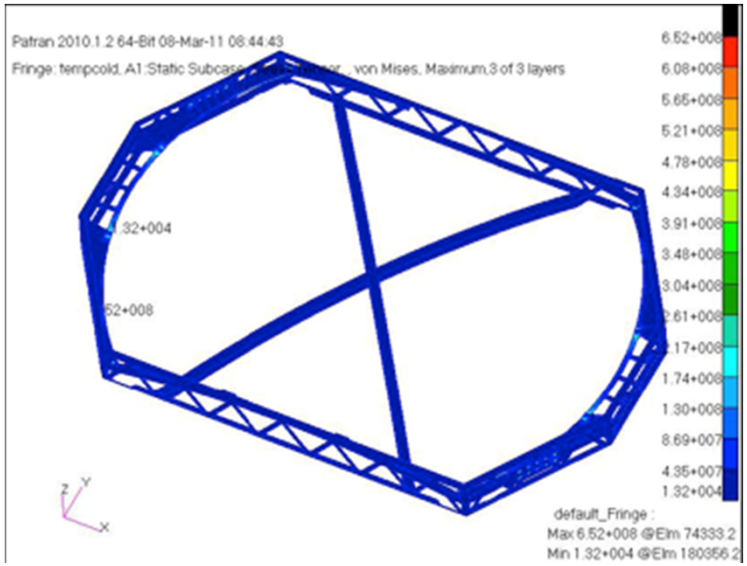
Maximum Displacement (meters)



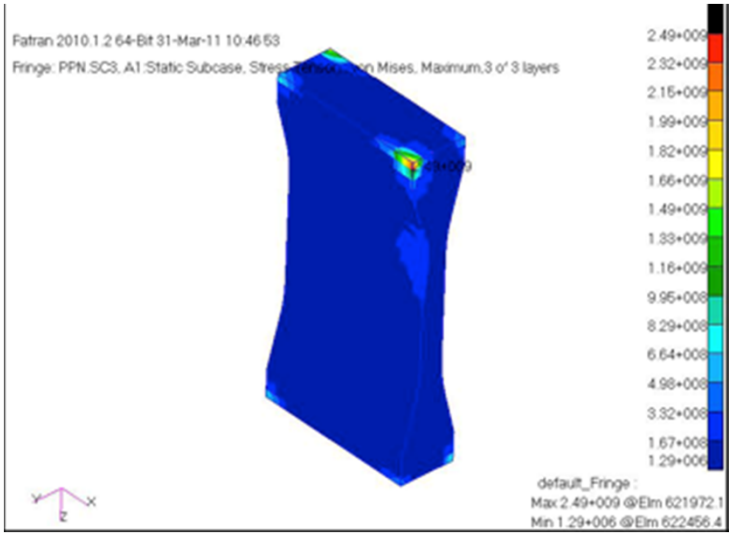
Thermal Analysis Results

Maximum stress (Pascals) for Thermal range -20 to +40 ˚C Assembled at room temperature





Flexure



Conclusions

- Majority of the design is showing positive safety margins
- Few areas with negative margins
  - ❖ Address in the next iteration of analysis
  - ❖ Many are due to the modeling
  - ❖ Applying loads simultaneously is conservative
- Minor changes in design and more detailed modeling and analysis should produce positive margins
- The thermal and structural issues identified in the analysis are similar and should be resolved with the same design/model modifications
- The masts need to be included in the next iteration